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# Dietary nitrate-induced increases in human muscle power: High versus low responders

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## ORIGINAL RESEARCH

## Dietary nitrate-induced increases in human muscle power: high versus low responders

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### Keywords

Fiber type, isokinetic dynamometry, nitric oxide, sex differences.

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## Introduction

Maximal neuromuscular power is an important determinant of athletic performance and is also highly significant from a clinical perspective, as reductions in power contribute to impaired quality of life, disability, and possibly

## Abstract

Maximal neuromuscular power is an important determinant of athletic performance and also quality of life, independence, and perhaps even mortality in patient populations. We have shown that dietary nitrate ( $\text{NO}_3^-$ ), a source of nitric oxide (NO), improves muscle power in some, but not all, subjects. The present investigation was designed to identify factors contributing to this interindividual variability. Healthy men ( $n = 13$ ) and women ( $n = 7$ ) 22–79 year of age and weighing 52.1–114.9 kg were studied using a randomized, double-blind, placebo-controlled, crossover design. Subjects were tested 2 h after ingesting beetroot juice (BRJ) either containing or devoid of  $12.3 \pm 0.8$  mmol of  $\text{NO}_3^-$ . Plasma  $\text{NO}_3^-$  and nitrite ( $\text{NO}_2^-$ ) were measured as indicators of NO bioavailability and maximal knee extensor speed ( $V_{\max}$ ), power ( $P_{\max}$ ), and fatigability were determined via isokinetic dynamometry. On average, dietary  $\text{NO}_3^-$  increased ( $P < 0.05$ )  $P_{\max}$  by  $4.4 \pm 8.1\%$ . Individual changes, however, ranged from  $-9.6$  to  $+26.8\%$ . This interindividual variability was not significantly correlated with age, body mass (inverse of  $\text{NO}_3^-$  dose per kg), body mass index (surrogate for body composition) or placebo trial  $V_{\max}$  or fatigue index (in vivo indicators of muscle fiber type distribution). In contrast, the relative increase in  $P_{\max}$  was significantly correlated ( $r = 0.60$ ;  $P < 0.01$ ) with the relative increase in plasma  $\text{NO}_2^-$  concentration. In multivariable analysis female sex also tended ( $P = 0.08$ ) to be associated with a greater increase in  $P_{\max}$ . We conclude that the magnitude of the dietary  $\text{NO}_3^-$ -induced increase in muscle power is dependent upon the magnitude of the resulting increase in plasma  $\text{NO}_2^-$  and possibly female sex.

even mortality in various patient populations (e.g., the elderly (Guralnik et al. 1994), heart failure (HF) patients (Hülsmann et al. 2004)). It is therefore noteworthy that recent studies have demonstrated that acute or chronic supplementation with dietary nitrate ( $\text{NO}_3^-$ ), a source of nitric oxide (NO) via the enterosalivary pathway

(Lundberg and Weitzberg 2009), can influence muscle contractile properties (Haider and Folland 2014; Coggan *et al.* 2015a,b; Justice *et al.* 2015; Rimer *et al.* 2016; Whitfield *et al.* 2017). In a previous study, for example, we found that acute ingestion of  $\text{NO}_3^-$  increased maximal knee extensor speed and power in healthy, untrained individuals by 11 and 6%, respectively, (Coggan *et al.* 2015b). We observed a similar dietary  $\text{NO}_3^-$ -induced enhancement of maximal neuromuscular power in athletes (Rimer *et al.* 2016), and an even greater increase (i.e., 13%) in patients with HF (Coggan *et al.* 2015a).  $\text{NO}_3^-$  (or nitrite ( $\text{NO}_2^-$ ))-induced improvements in muscle contractility have also been observed in some (Haider and Folland 2014; Justice *et al.* 2015; Whitfield *et al.* 2017), albeit not all (Hoon *et al.* 2015), recent studies of voluntary or electrically stimulated isometric exercise.

Based on these previous studies (Haider and Folland 2014; Coggan *et al.* 2015a,b; Justice *et al.* 2015; Rimer *et al.* 2016; Whitfield *et al.* 2017), it therefore appears that dietary  $\text{NO}_3^-$  can enhance the inherent contractile properties of human muscle. However, as with  $\text{NO}_3^-$ -induced improvements in endurance performance (Christensen *et al.* 2013; Boorsma *et al.* 2014) (or reductions in blood pressure (Kapil *et al.* 2010)), not all individuals seem to respond equally. Specifically, only about three-fourths of the subjects we have studied previously have demonstrated improvements in muscle speed and/or power with  $\text{NO}_3^-$  intake. The reason for this variability between individuals is not clear, but it may be related to the extent to which  $\text{NO}_3^-$  intake increases NO bioavailability. This hypothesis is suggested by the key role played by oral bacteria in reducing ingested  $\text{NO}_3^-$  to  $\text{NO}_2^-$ , the immediate precursor for NO synthesis via the enterosalivary pathway (Lundberg and Weitzberg 2009). Alternatively and/or in addition, based in part on animal studies it has been proposed that the effects of dietary  $\text{NO}_3^-$  supplementation are greatest in type II, or fast-twitch, muscle fibers (Jones *et al.* 2016). The interindividual variability in muscle power improvements that we have observed therefore may be related to differences in muscle fiber type distribution.

The purpose of this study was to test the hypothesis that interindividual differences in the effects of dietary  $\text{NO}_3^-$  on muscle function are related to interindividual differences in NO production and/or in the percentage of fast-twitch muscle fibers. To do so, we determined the relationship between changes in muscle power due to  $\text{NO}_3^-$  ingestion and markers of NO bioavailability (i.e., plasma  $\text{NO}_3^-$  and  $\text{NO}_2^-$  levels) and muscle fiber type (i.e., maximal knee extensor velocity ( $V_{\text{max}}$ ) and fatigability in the absence of  $\text{NO}_3^-$  intake) in a heterogeneous group of healthy men and women. We recruited subjects widely varying in other characteristics (e.g., age) as well, to determine whether there was any relationship between such factors and the

response to dietary  $\text{NO}_3^-$ . The results of this study provide insight into the mechanisms responsible for interindividual differences in the effects of  $\text{NO}_2^-$  supplementation on muscle power, which may prove useful in optimizing this intervention in both athletes and clinical populations.

## Methods

### Subjects

We studied 13 men and 7 women ranging in age from 22 to 79 (mean  $47 \pm 20$ ) years, in body mass from 52.1 to 114.9 (mean  $78.2 \pm 16.3$ ) kg, and in body mass index (BMI) from 19.1 to 32.6 (mean  $25.8 \pm 4.2$ )  $\text{kg/m}^2$ . All of the subjects were healthy, based upon medical history, physical examination, and standard blood chemistries. Although all were normally active, only two exercised regularly, and none were engaged in training for competitive sports. None of the subjects smoked. Additional exclusion criteria included use of drugs that can block reduction of  $\text{NO}_3^-$  and  $\text{NO}_2^-$  to NO (i.e., prescription sex hormones, antacids, proton pump inhibitors, or xanthine oxidase inhibitors) (Lundberg *et al.* 1994; Obach *et al.* 2004) or can potentiate the effects of the latter (i.e., phosphodiesterase inhibitors) (Webb *et al.* 1999). Women who were pregnant or lactating were also excluded. Approval for the study was obtained from the Human Subjects Office at Indiana University and the Human Research Protection Office at Washington University School of Medicine, and all subjects provided written, informed consent. Partial data from some of these subjects has been presented previously (Coggan *et al.* 2015b).

### Experimental design and protocol

Each subject was studied twice using a double-blind, placebo-controlled, randomized design. During one trial, subjects were tested after ingesting 140 mL of a commercial beetroot juice (BRJ) supplement (Beet It<sup>®</sup>, James White Drinks, Ipswich, UK) containing  $12.3 \pm 0.8$  mmol of  $\text{NO}_3^-$ . During the other trial, they ingested an equal volume of concentrated BRJ from which the  $\text{NO}_3^-$  had been removed by the manufacturer. A washout period of 1–2 weeks separated the two trials (i.e.,  $\text{NO}_3^-$  vs. placebo). Since use of an antibacterial mouthwash, tooth brushing, or chewing gum can block the conversion of  $\text{NO}_3^-$  to  $\text{NO}_2^-$  by oral bacteria (Lundberg *et al.* 1994; Govoni *et al.* 2008), subjects were instructed to avoid these behaviors on study days. They were also instructed to avoid high  $\text{NO}_3^-$  foods throughout the study, with adherence to this instruction verified by analysis of food records by a dietician.

Subjects arrived at the Clinical Research Unit in the morning after avoiding food, caffeine, or alcohol intake

for the previous 12 h. A catheter was first inserted in an antecubital vein and a blood sample obtained for subsequent measurement of plasma  $\text{NO}_3^-$  and  $\text{NO}_2^-$  concentrations via high-performance liquid chromatography (ENO-30, Eicom USA, San Diego, CA). These measurements were repeated and 2 h of quiet rest, after which the contractile properties of the knee extensor muscles of the subject's dominant leg were determined using an isokinetic dynamometer (Biodex System 4 Pro, Biodex Medical Systems, Shirley, NY) as previously described (Coggan *et al.* 2015a,b). Briefly, each subject performed 3–4 maximal knee extensions at angular velocities of 0, 1.57, 3.14, 4.71, and 6.28 rad/sec, with 2 min of rest between each set. The resulting torque data were filtered and smoothed to eliminate artifacts, after which peak power was calculated by multiplying the peak torque observed at each velocity by that velocity. The power-velocity data were then fit with a parabolic function to determine the subject's  $V_{\text{max}}$  and maximal power ( $P_{\text{max}}$ ). After an additional 2 min of rest, the subject performed 50 consecutive maximal knee extensions at an angular velocity of 3.14 rad/sec to determine their resistance to fatigue (i.e., fatigue index, =% decrease in power from first 1/3 to last 1/3 of the test) during repeated muscle contractions. Following a 10 min rest period, the final plasma samples were obtained after which the subject was fed a light meal and released.

### Data analysis

Statistical analyses were performed using GraphPad Prism version 7.02 (GraphPad Software, La Jolla, CA). Normality of data distribution was first tested using the D'Agostino-Pearson omnibus test. Data from the placebo and  $\text{NO}_3^-$  trials were subsequently compared using two-way (treatment x order) ANOVA, with subject as a repeated measures factor within treatment. Intraclass correlation coefficients were calculated from the ANOVA results to quantify the reliability of the data. Standard Pearson product correlations were calculated to explore the

relationship between relative changes in  $P_{\text{max}}$  as the dependent variable and sex, age, body mass (inverse to  $\text{NO}_3^-$  dose in  $\mu\text{mol/kg}$ ), BMI, placebo trial  $V_{\text{max}}$ , placebo trial fatigue index (in vivo indicators of muscle fiber type distribution), percent change in plasma  $\text{NO}_3^-$ , or percent change in plasma  $\text{NO}_2^-$  as independent variables. The overall false discovery rate was limited to 10% using the Benjamini–Hochberg procedure. As this was an exploratory study, stepwise forward regression was also employed using the same dependent and independent variables, with the  $P$  value to enter the model similarly set to 0.10.

### Results

The effects of ingesting BRJ without or with  $\text{NO}_3^-$  on plasma  $\text{NO}_3^-$  and  $\text{NO}_2^-$  concentrations are shown in Table 1. No significant changes occurred in the placebo trial, whereas during the  $\text{NO}_3^-$  trial, both  $\text{NO}_3^-$  and  $\text{NO}_2^-$  increased significantly. This was accompanied by a significant ( $P < 0.05$ ) elevation in  $V_{\text{max}}$ , which increased from  $12.3 \pm 2.5$  (range: 9.3–20.2) rad/sec in the placebo trial to  $13.2 \pm 3.1$  (range: 8.4–20.2) rad/sec in the  $\text{NO}_3^-$  trial.  $P_{\text{max}}$  also increased significantly ( $P < 0.05$ ), that is, from  $6.3 \pm 2.3$  (range: 2.8–10.7) to  $6.6 \pm 2.4$  (range: 2.7–11.8) W/kg. Individual changes varied from  $-9.6$  to  $+26. \%$  (Fig. 1). On the other hand, the fatigue index was unaltered by  $\text{NO}_3^-$  intake, averaging  $61 \pm 13$  (range: 34–78) and  $61.6 \pm 13.5$  (range: 32–78)% during the placebo and  $\text{NO}_3^-$  trials, respectively. All three performance measures were highly reliable, with intraclass correlation coefficients of 0.94, 0.98, and 0.89 for  $V_{\text{max}}$ ,  $P_{\text{max}}$ , and fatigue index, respectively. No adverse effects were observed. These observations confirm and extend our previous findings (Coggan *et al.* 2015a,b; Rimer *et al.* 2016). The remainder of our effort therefore focused upon attempting to elucidate the factors responsible for the marked variability between subjects in the response to  $\text{NO}_3^-$  intake.

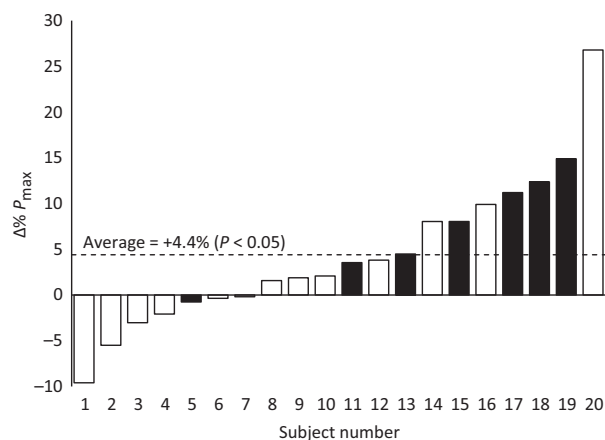
In univariable analyses, the relative increase (i.e.,  $\Delta\%$ ) in  $P_{\text{max}}$  due to dietary  $\text{NO}_3^-$  ingestion was not

**Table 1.** Changes in plasma  $\text{NO}_3^-$  and  $\text{NO}_2^-$  in response to  $\text{NO}_3^-$

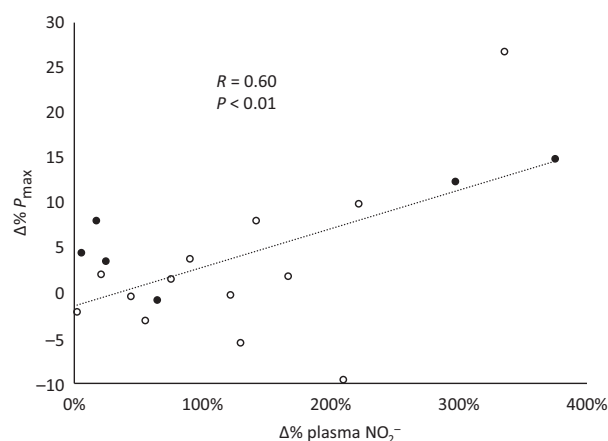
	Trial	Time point			
		Pre	1 h	2 h	10 min post
Plasma $\text{NO}_3^-$ ( $\mu\text{mol/L}$ )	Placebo	$26 \pm 11$	$23 \pm 9$	$22 \pm 7$	$23 \pm 11$
	Nitrate	$30 \pm 18$	$334 \pm 111^\dagger$	$351 \pm 74^\dagger$	$346 \pm 91^\dagger$
Plasma $\text{NO}_2^-$ ( $\mu\text{mol/L}$ )	Placebo	$0.29 \pm 0.22$	$0.30 \pm 0.26$	$0.30 \pm 0.28$	$0.29 \pm 0.36$
	Nitrate	$0.36 \pm 0.40$	$0.44 \pm 0.33^*$	$0.47 \pm 0.34^\dagger$	$0.57 \pm 0.32^\dagger$

Values are mean  $\pm$  SD for  $n = 19$ .

Nitrate trial significantly higher than Placebo trial at same time point: \* $P < 0.01$ ,  $^\dagger P < 0.0001$ .



**Figure 1.** Individual relative changes in maximal knee extensor power ( $P_{\max}$ ) in response to dietary  $\text{NO}_3^-$  intake. Open bars, male subjects. Closed bars, female subjects. The overall average response is also shown (dashed line).



**Figure 2.** Relationship of relative changes in maximal knee extensor power ( $P_{\max}$ ) to relative changes in plasma  $\text{NO}_2^-$  concentration in response to dietary  $\text{NO}_3^-$  intake. Open symbols, male subjects. Closed symbols, female subjects. Plasma samples from one female subject were not available for analysis; data for the remaining 19 subjects are therefore shown.

significantly correlated with sex, age, body mass, or BMI, or with placebo trial  $V_{\max}$  or fatigue index (Table 2). The relative magnitude of the increase in  $P_{\max}$  was also not correlated with the relative change in plasma  $\text{NO}_3^-$  concentration (Table 2). There was, however, a significant correlation between the relative increase in  $P_{\max}$  and the relative increase in plasma  $\text{NO}_2^-$  concentration due to  $\text{NO}_3^-$  intake (Table 2; Fig. 2). The relative change in plasma  $\text{NO}_2^-$  concentration was also the strongest predictor of relative changes in  $P_{\max}$  in the multivariable analysis (Table 3). Female sex also tended to be a positive

predictor of relative increases in  $P_{\max}$  in the multivariable analysis (Table 3). In keeping with this, female subjects tended (i.e.,  $P = 0.06$  by Fisher's exact test) to be more likely to exhibit a greater-than-average increase in  $P_{\max}$ , that is, to be “high responders” (Fig. 2). Taken together, the relative change in plasma  $\text{NO}_2^-$  concentration and subject sex explained  $\sim 40\%$  of the interindividual variation in the effect of  $\text{NO}_3^-$  intake on muscle power (i.e.,  $R^2$  of multivariable regression = 0.38).

## Discussion

The purpose of this study was to identify (if possible) factors contributing to interindividual variability in improvements in muscle contractile function resulting from dietary  $\text{NO}_3^-$  intake. Based on previous research, we hypothesized that such differences would be related to differences between individuals in markers of NO bioavailability and/or muscle fiber type. Consistent with the first hypothesis, we found a significant correlation between the relative increase in  $P_{\max}$  and the relative increase in plasma  $\text{NO}_2^-$  concentration due to  $\text{NO}_3^-$  ingestion. Our second hypothesis, however, was not supported, as there was no association between the increase in  $P_{\max}$  and baseline  $V_{\max}$  or fatigue index, *in vivo* indicators of muscle fiber type distribution (see below). Finally, our data provide preliminary support for the novel hypothesis that, at least in terms of improvements in maximal neuromuscular power, women are more likely than men to benefit from dietary  $\text{NO}_3^-$  supplementation.

Reduction in  $\text{NO}_3^-$  to  $\text{NO}_2^-$  by oral bacteria plays a critical role in the production of NO via the enterosalivary pathway (Lundberg et al. 1994; Govoni et al. 2008; Lundberg and Weitzberg 2009). In fact, this step appears to be possibly rate-limiting, as demonstrated by the much smaller increase in plasma  $\text{NO}_2^-$  versus  $\text{NO}_3^-$  following  $\text{NO}_3^-$  ingestion (Table 1). Accordingly, previous studies have observed a significant correlation between the magnitude of the increase in plasma  $\text{NO}_2^-$  following  $\text{NO}_3^-$  ingestion and the improvement in endurance performance ability (Wilkerson et al. 2012; Hoon et al. 2014). Our results are similar, as we found that interindividual differences in how much plasma  $\text{NO}_2^-$  concentration was elevated by  $\text{NO}_3^-$  intake accounted for about one-third of the variation between individuals in the increase in  $P_{\max}$ . It is possible that this significant correlation reflects a direct effect of  $\text{NO}_2^-$  on muscle contractility. Indeed, in cardiac muscle  $\text{NO}_2^-$  has been shown to nitrosylate cysteine residues of various membrane proteins independently of NO (Montesanti et al. 2014). In skeletal muscle, however, S-nitrosylation is thought to inhibit contractile function; stimulatory effects are held to be the result of NO-dependent soluble guanyl cyclase (sGC)/



**Table 2.** Pearson-product correlation coefficients between  $\Delta\%$  Pmax and potential explanatory variables.

Sex	Age	Body mass	BMI	Placebo $V_{\max}$	Placebo fatigue index	$\Delta\%$ $\text{NO}_3^-$	$\Delta\%$ $\text{NO}_2^-$
0.31	-0.16	-0.16	0.10	0.08	-0.25	-0.05	0.60*

\* $P < 0.01$ .**Table 3.** Results of stepwise forward regression.

Predictor	Beta coefficient	SE	Lower 95% CI	Upper 95% CI	<i>t</i>	<i>P</i>
$\Delta\%$ $\text{NO}_2^-$	0.038	0.014	0.011	0.064	2.81	0.005
Sex	0.056	0.032	-0.006	0.118	1.76	0.079

cyclic GMP (cGMP)/protein kinase G (PKG) signaling (Maréchal and Gaily 1999). A direct effect of  $\text{NO}_2^-$  would therefore seemingly not explain the positive correlation we observed between changes in plasma  $\text{NO}_2^-$  and changes in Pmax. Rather, this observation is consistent with our first hypothesis that interindividual differences in the availability of NO itself contribute to interindividual differences in the extent to which dietary  $\text{NO}_3^-$  intake increases muscle power.

Although we were able to at least partially confirm our first hypothesis, our data do not support our second hypothesis, which was that individuals with a greater percentage of fast-twitch fibers would demonstrate a greater dietary  $\text{NO}_3^-$ -induced increase in muscle power. In particular, we found no correlation between the increase in Pmax and  $V_{\max}$  or fatigue index during the placebo trial. Although indirect, numerous previous studies have demonstrated that these (or comparable) measurements are significantly correlated with muscle fiber type (e.g., Coyle et al. 1979; Ivy et al. 1981; McCartney et al. 1983). Moreover,  $V_{\max}$  and fatigue index were highly characteristic of a given subject, as indicated their high intraclass correlation coefficients. Given the strength of the association between muscle fiber type, speed, and fatigability found in previous studies (Coyle et al. 1979; Ivy et al. 1981; McCartney et al. 1983) along with the reproducibility of our measurements and the >2-fold range in  $V_{\max}$  and fatigue index during the placebo trial, it seems unlikely that the lack of correlation of the latter measures with the magnitude of the increase in Pmax with  $\text{NO}_3^-$  ingestion is the result a type II statistical error. On the other hand, the premise that dietary  $\text{NO}_3^-$  supplementation selectively targets fast-twitch fibers is based largely on animal studies of muscle blood flow and oxygenation during aerobic exercise, for example, (Ferguson et al. 2015), and is only indirectly supported by human data. Specifically, Bailey et al. (2015) demonstrated dietary

$\text{NO}_3^-$ -induced differences in muscle oxygenation, whole-body  $\text{VO}_2$  kinetics, and performance during cycling when pedaling at 115 rpm but not at 35 rpm. Breese et al. (2013) reported similar benefits during the transition from moderate to high-intensity exercise but not from low to moderate intensity exercise. These data, along with the fact that we have previously reported that  $\text{NO}_3^-$  improves muscle function only at higher velocities (Coggan et al. 2015a,b), have been interpreted by Jones et al. (2016) as reflecting enhanced recruitment of fast-twitch fibers at a higher velocities/intensities of exercise. It is unclear, however, whether altering pedaling rate in fact changes the pattern of motor unit recruitment (Ahluquist et al. 1992). Similarly, the relationship between exercise intensity and  $\text{O}_2$  flux is complex, with motor unit recruitment being only one influencing factor (Jones et al. 2011). Finally, in both fast- and slow-twitch muscle NO seems to improve contractile function by increasing the rate of cross-bridge cycling, not the amount of force per cross-bridge (Maréchal and Gaily 1999). The resultant shift in the force-velocity (and hence power-velocity) curve, and not a selective impact only in fast-twitch fibers, may therefore explain why we have previously observed statistically significant  $\text{NO}_3^-$ -induced improvements in power only at higher speeds of contraction (Coggan et al. 2015a,b). The notion that dietary  $\text{NO}_3^-$  affects only, or even primarily, human fast-twitch fibers would therefore still seem equivocal.

An unexpected observation in this study was that, at least in terms of improvements in Pmax, women seem to benefit more than men from dietary  $\text{NO}_3^-$  intake. Specifically, although not significant in the univariable analyses, female sex was the only predictor other than plasma  $\text{NO}_2^-$  concentration selected by the stepwise forward regression procedure. Female subjects also tended to be more likely to be “high responders” to  $\text{NO}_3^-$  supplementation, with five out of seven demonstrating greater-than-

average increases in  $P_{\max}$ . This was true even though  $\text{NO}_3^-$  intake increased plasma  $\text{NO}_2^-$  concentration similarly in both women (i.e.,  $+131 \pm 162\%$ ) and men (i.e.,  $+124 \pm 93\%$ ). Previous studies of the effects of dietary  $\text{NO}_3^-$  on exercise performance have included only male subjects (e.g., Christensen *et al.* 2013; Boorsma *et al.* 2014; Haider and Folland 2014; Hoon *et al.* 2014; Bailey *et al.* 2015; Whitfield *et al.* 2017), or have not commented on possible sex-related differences (e.g., Breese *et al.* 2013; Hoon *et al.* 2015). It has been reported, however, that plasma  $\text{NO}_3^-$  (Jilma *et al.* 1996; Ghasemi *et al.* 2008) and/or breath  $\text{NO}$  levels (Jilma *et al.* 1996; Olivieri *et al.* 2006) are lower in women. The reason for this difference is not known, but it may be due to suppression of  $\text{NO}$  production by progesterone (Scichilone *et al.* 2013) and/or a sex-related difference in the distribution of a polymorphism in the neuronal  $\text{NO}$  synthase (NOS) gene (Grasemann *et al.* 2003). Regardless, lower  $\text{NO}$  bioavailability under baseline conditions could explain why the women seemed to be more responsive to dietary  $\text{NO}_3^-$  intake. Indeed, we have previously observed an approximately twofold greater dietary  $\text{NO}_3^-$ -induced improvement in muscle power in patients with HF (Coggan *et al.* 2015a) compared to healthy control subjects (Coggan *et al.* 2015b) or athletes (Rimer *et al.* 2016), presumably because of diminished NOS-mediated  $\text{NO}$  production (Katz *et al.* 1999) and enhanced  $\text{NO}$  destruction (Münzel *et al.* 2015) in patients with HF. Somewhat along the same lines, Kapil *et al.* (2010) found that changes in blood pressure in response to  $\text{NO}_3^-$  ingestion were greatest in individuals with lower baseline plasma  $\text{NO}_2^-$  concentrations (and higher baseline blood pressures), although in this case it was men who benefited the most. In any case, future studies should more directly address possible sex-related differences in the effects of  $\text{NO}_3^-$  ingestion on exercise performance.

There are a number of limitations to this study. The most obvious is that muscle biopsies were not performed to directly determine fiber type distribution, which potentially could have revealed a relationship between the percentage of fast-twitch fibers and the relative increase in  $P_{\max}$ . Our study also included a relatively small number of individuals, only two of which were regular exercisers and none of whom were presently competing in endurance sports. Whether similar results would be obtained in a larger group of subjects and/or among athletes therefore cannot be determined from the present data. Although we used a randomized, placebo-controlled, cross-over design, there were no significant order effects, and  $P_{\max}$ ,  $V_{\max}$ , and fatigue index proved to be highly reliable, it is possible that inclusion of a familiarization trial would have altered the results (especially in the several subjects

in whom  $\text{NO}_3^-$  ingestion seemed to impair muscle function.

Finally, although we have been able to identify two factors (i.e., plasma  $\text{NO}_2^-$  concentration and possibly subject sex) contributing to interindividual differences in the effects of dietary  $\text{NO}_3^-$  on muscle contractile function, it must be emphasized that over half of this variability remains unexplained. Of course, some of this variability represents normal day-to-day variation in human performance (Coggan and Costill 1984), and is not due to  $\text{NO}_3^-$  ingestion *per se*. Such random variability, however, could not explain the wide range of responses we observed, and as indicated previously measurement of  $P_{\max}$  was highly reproducible. Additional studies measuring  $\text{NO}_3^-$  reduction in the mouth as well as  $\text{NO}/\text{sGC}/\text{cGMP}/\text{PKG}$  signaling in muscle may provide further insight into the mechanism(s) responsible for this marked interindividual variability in the effects of dietary  $\text{NO}_3^-$  on muscle power.

In summary, in this study we sought to identify factors influencing the magnitude of the improvement in muscle power due to dietary  $\text{NO}_3^-$  intake. Our findings indicate that variable increases in  $\text{NO}$  bioavailability, as indicated by changes in plasma  $\text{NO}_2^-$  concentration, along with subject sex account for ~40% of this variability. On the other hand, interindividual differences in muscle fiber type do not appear to be important. Much of the variation in response between individuals remains unexplained.

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## Conflict of Interest

None to declare.

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