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Original Research

Non-local Muscle Fatigue in Young and Middle-Aged Women following Fast-Paced Walking

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Abstract

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Non-local muscle fatigue (NLMF) has been well-studied in young individuals following acute, higher intensity exercise; however, the effects of age on NLMF are unclear and limited research exist in women. Research examining age-related differences in NLMF following tasks mimicking everyday life such as fast-paced walking is needed. The purpose of this study was to determine the potential differences in NLMF for maximal and rapid force capacity between young and middle-aged women following an acute bout of fast-paced walking. Young (YW; n=16; 21±2 yrs) and post-menopausal, middle-aged (MW; n=14; 55±3 yrs) women completed a testing visit following a familiarization session. Handgrip testing was performed before and after a 6-min, fast-paced walking task. Maximal force, and early (0-100 ms) and late (0-200 ms) rapid force metrics were calculated from the force-time curve captured during handgrip testing. Rating of perceived exertion (0-10) was also obtained. Two-way mixed group × time ANOVAs were used to compare changes between groups. RPE was similar for YW (3.00±1.16) and MW (3.29±1.45) ($p=0.560$; $d=0.22$). Maximal force increased in YW ($p=0.024$; $d=0.52$) but remained unchanged in MW ($p=0.092$; $d=0.56$). Peak ($p<0.001$; $\eta_p^2=0.477$) and early ($p<0.001$–$p=0.002$; $\eta_p^2 = 0.284$–0.365) rapid force decreased similarly for both groups. Late rapid force remained unchanged ($p=0.210$–0.688; $\eta_p^2=0.055$–0.006). Despite no effect of age, NLMF was exhibited solely through early rapid force capacity following moderate intensity fast-paced walking. The divergent responses between maximal and rapid force are an important consideration for future research, given the implications for physical function in older populations.

Keywords: Rate of force development (RFD), aging, muscle strength, handgrip, post-menopause

Introduction

Non-local muscle fatigue (NLMF) refers to the decrease in performance of a non-exercised muscle, located superiorly, inferiorly, contralaterally or ipsilaterally from the fatigued muscle group.[1] The underlying mechanisms of NLMF are believed to be mediated through the central nervous system,[2] metabolite accumulation (indirect),[3] or psychological factors.[4] Though several studies have indicated the presence of NLMF,[5-7] a recent meta-analysis concluded that the evidence for NLMF is inconsistent and appears to be dependent upon the outcome of interest.[8] This is at least partially due to a lack of diversity amongst studies; indeed, it was also determined there are several gaps in the literature including the influence of sex and age. Specifically, studies on NLMF rarely include women and age-related comparisons are absent.[8] Findings for the

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limited work comparing sexes is equivocal with some studies indicating greater NLMF in men for the lower-body[9,10] and other work showing no difference for upper-body musculature.[11] To date, NLMF research has been performance-oriented such that fatigue is typically induced by either isolated muscle contractions[9,12] or cycling[13,14] in recreationally active or trained individuals. Greater diversity is needed in NLMF research to gain understanding regarding the existence of NLMF and its broader implications. It is critical to examine NLMF following tasks more closely resembling daily life in untrained populations, given they are more susceptible to fatigue.

There is relatively little known regarding the task-specificity of NLMF, but previous work has provided some insight. For example, NLMF of the lower-body was greater following higher intensity fatiguing tasks[6,7] however, this was not the case when the upper-body was tested.[15] Additionally, high or maximal intensity exercise[7] tends to demonstrate greater NLMF compared to lower intensity exercise.[16,17] More recently, greater NLMF was exhibited when testing during high-velocity isokinetic contractions, however, this effect was only shown for fatigue index (i.e., strength decline over 15 repetitions) and not discrete muscle strength.[5] Similarly, studies examining running[18,19] and cycling[20] tasks have not shown NLMF when tested as a discrete outcome. Indeed, a recent meta-analysis[8] concluded that NLMF appears to be more prominent when evaluated as endurance-based outcomes compared to discrete outcomes characterizing maximal strength or power. However, these findings are based on young and recreationally active or athletic male samples. Less is clear in untrained, middle-aged or older populations, and it is possible that NLMF may be more prominent following submaximal activity in these age groups. Further, research examining discrete measures of NLMF has almost exclusively assessed maximal strength, thus there is limited information on rapid force measures such as rate of force development (RFD).[21] Rapid force production may be particularly vulnerable to NLMF, specifically during the early phase (0-100 ms), as it is more strongly influenced by initial neural drive to skeletal muscle.[22,23] It is important to determine the effects of NLMF on rapid force production in older populations considering the relevance of this muscle function parameter for physical function.[24]

To the best of our knowledge, no study has examined the effect of age on NLMF. There are prominent age-related differences for the effects of fatigue on the exercising limb, so it is prudent to determine if the same is true for NLMF. For example, older adults are more fatigable following high-velocity, dynamic contractions[25,26] compared to young adults yet less fatigable following sustained isometric exercises.[27,28] Evidence related to fatigue of the previously exercised muscle,[29] nevertheless NLMF, in middle-aged adults is scant yet critical to understanding early, age-related changes relevant for physical function. One of the few studies comparing fatigue responses for young and middle-aged individuals found no age-related difference in a mixed-sex cohort.[30] However, only maximal strength was assessed, and it is possible that RFD may respond differently given its greater vulnerability to fatigue.[31,32] A significant event for middle-aged women is menopause, which could alter the response of the central nervous system to fatigue, at least in part, due to the role of estrogen on neural excitiablity.[33,34] Previous longitudinal research has shown the detrimental effect of the menopausal transition on physical function,[35,36] underscoring the need for more research in post-menopausal, middle-aged women. Further, as opposed to the high-intensity, isolated exercise models in previous research, it is critical to determine if NLMF is demonstrated following a submaximal task representative of daily life in this population. This insight would be valuable towards understanding the implications of NLMF following more common physical activity, such as fast-paced walking, and the influence of age. Thus, the purpose of this study was to determine the potential differences in NLMF for maximal

and rapid force capacity between young and middle-aged women following an acute bout of fast-paced walking. We hypothesized that rapid force measures would be more susceptible to age-related differences in NLMF than maximal force.

Methods

Participants

Thirty-one, healthy young (YW; n = 16, 21 ± 2 yrs) and post-menopausal, middle-aged (MW; n = 14, 55 ± 3 yrs) women participated in this study (Table 1). G*Power (v. 3.1.9.4) software indicated a total sample size of 30 would detect a medium effect size (f = 0.27) with a statistical power of 0.80 for a two-way analysis of variance. This effect size was deemed justifiable based on practical meaningfulness and feasibility of the sample size due to resource limitations. Participants were excluded if they were active student-athletes or members of a club sports team, actively taking hormone-replacement therapy, had uncontrolled hypertension, were pregnant, or had suffered a lower-body injury within the previous six months. Participants completed the International Physical Activity Questionnaire[37] to estimate baseline physical activity (MET-hrs/week). YW were required to be taking the same monophasic birth control contraceptive at least the previous six months leading up to the study and MW had to be at least six months post-menopausal at time of study inclusion. This study was approved by the Kennesaw State University Institutional Review Board prior to data collection. This research was carried out fully in accordance with the ethical standards of the International Journal of Exercise Science.[38] All participants provided oral and written consent prior to beginning the study.

Protocol

Participants visited the laboratory two times, separated by at least 3 days but no more than 7 days. The first visit included body composition testing and familiarization with handgrip testing. The second visit included handgrip testing before and after a fast-paced walking task. YW were instructed to schedule their second visit during the last 14 days of the pill consumption phase of their oral contraceptive cycle (i.e., the two weeks prior to the placebo pill period) to minimize fluctuations in endogenous hormones.[39,40] Participants were requested to avoid alcohol and strenuous activity for 24 hrs and caffeine for 12 hrs prior to all visits. Participants received compensation upon completion of the study.

Body mass and height were recorded using a digital physician scale (Tanita WB 3000, Arlington Heights, IL, USA). Body fat percentage was recorded using bioelectrical impedance analysis (InBody770, InBody Co., Cerritos, CA, USA).

The fast-paced walking task consisted of a 6-min walk test following standardized procedures.[41] This standardized protocol was chosen to support replication in future studies and because it is fairly representative of daily activity. The duration is comparable to the average walking time to and from transit according to the National Household Travel Survey.[42] Subjects were instructed to "cover as much distance as possible" while walking between two cones set 15.2 m apart. Testers gave standardized encouragement ("You're doing great," and "Keep up the good work") and updates to participants regarding time elapsed and remaining every sixty seconds. Rating of perceived exertion (RPE) (Category Ratio Scale-10)[43] was recorded immediately after the walking task.

A Jamar style hydraulic handgrip dynamometer (Fabrication Enterprises, White Plains, NY, USA) was used for testing. Participants performed a warm-up consisting of 2 submaximal isometric contractions at 50% and a third at 75% of perceived maximal effort. For baseline testing, participants performed 3, 3-4 sec rapid maximal voluntary isometric contractions while seated and the elbow at ~90° separated by 1 min of rest. A single maximal voluntary isometric contraction was performed 3 min after the walking task for post testing due to the time needed to travel between the walking corridor and testing location. Subjects were instructed to squeeze the handgrip dynamometer "as hard and as fast as possible" with the dominant hand. Strong verbal encouragement and visual biofeedback was provided during testing.

The analog force output was recorded at 2 kHz through an AD converter and subsequent data analysis was performed using custom written software (LabVIEW, National Instruments, Austin, TX). The force signal was corrected for the baseline gripping force and then digitally filtered with a zero lag, low-pass (150 Hz)[44] Butterworth filter. Maximal force was recorded as the highest rolling 500 ms average and absolute force at 50 (F_{50}), 100 (F_{100}), and 200 ms (F_{200}) was obtained as well. RFD from 0-50 ms (RFD_{0-50}), 0-100 ms (RFD_{0-100}), and 0-200 ms (RFD_{0-200}), as well as peak RFD (RFD_{pk}) were derived from the linear slope of the force-time curve ($\Delta force/\Delta time$). RFD_{pk} was determined as the highest rolling 10 ms linear slope. Contraction onset was set at 1 Nm for all rapid force outcomes. Given the primary interest in rapid force production, the MVIC producing the highest RFD_{pk} was used as the pre-test value for subsequent analysis.

Statistical Analysis

Normality of data was confirmed via skewness and kurtosis. Specifically, skewness and kurtosis values were divided by their standard error and a threshold of 1.96 was used to determine non-normality.[45] Independent samples t-tests were used to compare groups at baseline. Two-way mixed ANOVAs [group (young vs. middle-age) × time (PRE vs. POST)] with group as a between-subjects factor were used to assess changes between groups across time. Levene's test was used to assess homogeneity of variance. In the case of significant interactions, Bonferroni adjusted pairwise comparisons for the simple effects were examined. Partial eta squared (η_p^2) was used for ANOVA analyses and <0.06, 0.07 – 0.14, and >0.14 indicated small, medium, and large effect sizes, respectively. Cohen's *d* was used for pairwise comparisons with 0.20, 0.50, and 0.80 indicating the same effect sizes, respectively. All statistical analyses were performed with SPSS version 29 (IBM Corporation, Chicago, IL). An alpha level of $p \leq 0.05$ was used to indicate statistical significance. Data are reported as mean ± SD in text and means with individual level data are shown in figures.

Results

Characteristics for each group are presented in Table 1. Middle-aged women demonstrated a greater body mass index ($p = 0.037$; $d = 0.80$) and body fat % ($p = 0.002$; $d = 1.24$) but other characteristics were similar between groups. All measures of maximal ($p = 0.573$; $d = 0.20$) and rapid force outcomes ($p = 0.426$; $d = 0.29$ – $p = 0.553$; $d = 0.22$) were similar between groups at baseline. RPE was similar between groups following the fast-paced walking task ($p = 0.560$; $d = 0.22$) (Table 1).

Table 1. Characteristics for young (YW) and middle-aged women group.

Variable	YW (n = 16)	MW (n = 14)	p-value and Effect Size
Body mass (kg)	63.46 ± 6.97	69.10 ± 14.17	p = 0.193 *d* = 0.52
BMI (kg/m^2)	23.56 ± 3.02	26.80 ± 4.98	**p = 0.037*** *d* = 0.80
Body fat (%)	28.58 ± 7.22	36.89 ± 6.09	**p = 0.002*** *d* = 1.24
MET (hrs/wk)	70.69 ± 89.24	65.85 ± 55.54	p = 0.862 *d* = 0.06
6MWT (m)	590.51 ± 48.49	581.24 ± 42.90	p = 0.586 *d* = 0.20
RPE (au)	3.00 ± 1.16	3.29 ± 1.45	p = 0.560 *d* = 0.22

BMI = body mass index, MET = metabolic equivalent of task, 6MWT = 6-min walk test, RPE = rating of perceived exertion
*Significantly greater in middle-aged women

Data for maximal and rapid force outcomes and ANOVA findings are presented in Table 2. A two-way interaction (p = 0.007; η_p^2 = 0.231) was only demonstrated for maximal force as YW demonstrated an increase (p = 0.024; *d* = 0.52; +4.9%) but MW exhibited no change (p = 0.092; *d* = 0.56; -4.0%) (Table 2; Figure 1). Main effects for time indicated similar decreases in each group for early (0-100 ms) rapid force outcomes, but no changes were shown for later rapid force outcomes (Table 2; Figure 1 and 2).

Table 2. Maximal and rapid force outcomes before and after the fast-paced walking task for young (YW) and middle-aged women (MW).

Variable	YW (n = 16)		MW (n = 14)		Two-way Interaction	Time Effect
	Pre	Post	Pre	Post		
Maximal Force (kg)	30.34 ± 3.02	31.82 ± 3.91	29.43 ± 5.46	28.27 ± 6.19	**p = 0.007*** η_p^2 = 0.231	p = 0.729 η_p^2 = 0.004
RFD_{pk} (kg·s^{-1})	324.03 ± 72.62	296.97 ± 69.78	305.40 ± 88.01	255.76 ± 84.00	p = 0.148 η_p^2 = 0.073	**p < 0.001*** η_p^2 = 0.477
RFD_{0-50} (kg·s^{-1})	250.87 ± 70.49	218.28 ± 76.72	231.44 ± 87.13	178.42 ± 71.41	p = 0.346 η_p^2 = 0.032	**p < 0.001*** η_p^2 = 0.365
RFD_{0-100} (kg·s^{-1})	234.81 ± 45.52	223.34 ± 51.02	222.09 ± 55.96	196.04 ± 60.80	p = 0.206 η_p^2 = 0.056	**p = 0.002*** η_p^2 = 0.284
RFD_{0-200} (kg·s^{-1})	139.61 ± 21.58	145.04 ± 25.72	133.26 ± 25.13	130.42 ± 32.20	p = 0.205 η_p^2 = 0.057	p = 0.688 η_p^2 = 0.006
F_{50} (kg)	12.87 ± 3.16	11.45 ± 3.45	11.91 ± 3.88	9.62 ± 3.32	p = 0.356 η_p^2 = 0.030	**p < 0.001*** η_p^2 = 0.361
F_{100} (kg)	22.31 ± 3.77	21.36 ± 4.44	21.19 ± 5.01	18.68 ± 5.22	p = 0.142 η_p^2 = 0.076	**p = 0.002*** η_p^2 = 0.287
F_{200} (kg)	28.05 ± 3.88	28.26 ± 4.48	26.72 ± 5.15	25.20 ± 5.92	p = 0.102 η_p^2 = 0.092	p = 0.210 η_p^2 = 0.055

RFD = rate of force development
*indicates significant (p < 0.05).

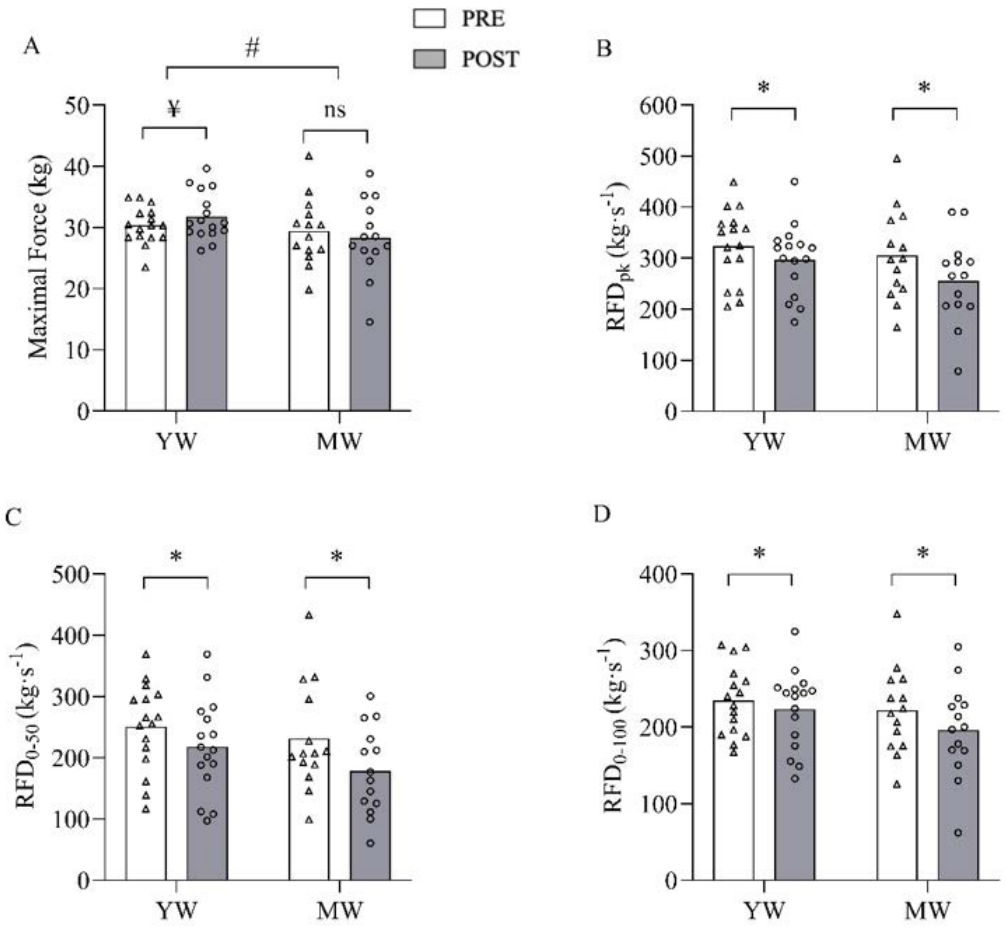

Figure 1. Maximal force (A), rate of force development at its peak (RFD_{pk}) (B), from 0-50 ms (RFD_{0-50}) (C), and from 0-100 ms (RFD_{0-100}) (D) before and after fast-paced walking in young (YW) and middle-aged (MW) women. *indicates similar decreases between groups ($p < 0.05$). # indicates two-way interaction ($p < 0.05$). ¥ indicates increases in YW only ($p < 0.05$).

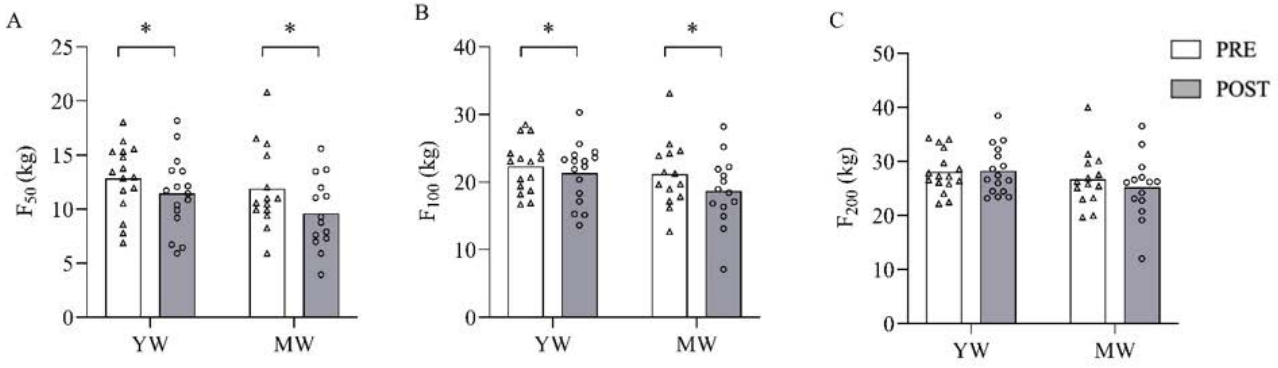

Figure 2. Absolute force at 50 ms (F_{50}) (A), 100 ms (F_{100}) (B), and 200 ms (F_{200}) (C) before and after fast-paced walking in young (YW) and middle-aged (MW) women. *indicates similar decreases between groups ($p < 0.05$).

Discussion

The purpose of this study was to determine the potential differences in NLMF of maximal and rapid force capacity between young and middle-aged women following an acute bout of fast-paced walking. Previous research on NLMF has focused on young, recreationally trained or athletic populations using maximal or high intensity structured exercise protocols eliciting substantial fatigue. This work expands on the topic of NLMF to untrained individuals and probes its implications following fast-paced walking requiring modest exertion. The fast-paced walking task used in the current study elicited an average RPE of 3, thus it was moderate in intensity.[43] While not "heavily" fatiguing, this level of exertion is representative of daily activities and supports the ecological validity of the walking task. The primary novel finding of this study was that NLMF was exhibited but only through early, rapid force outcomes during handgrip testing, and these reductions were similar in young and middle-aged women. Neither maximal force nor late phase rapid force production (>100 ms after contraction onset) were affected in either age group. These findings indicate no effect of age for NLMF, at least between young and middle-aged women, but greater susceptibility of NLMF for rapid force outcomes as compared to maximal force.

Our finding that NLMF was not demonstrated through measurement of maximal force is similar to others examining this outcome after endurance based fatiguing protocols in male participants who are recreationally or highly trained. Previous research has failed to demonstrate NLMF following prolonged running[18] or cycling.[19,20] Collectively, this provides further support for the notion that discrete measures of maximal strength are not affected by NLMF,[8] and our findings extend this to women and middle-aged adults. An interesting finding of this study was the decrease in rapid force production, despite maximal force not expressing NLMF. Research examining the effect of NLMF on rapid versus maximal force production is limited.[21,46] Miller et al. examined these outcomes following low-intensity eccentric and concentric exercise in recreationally active young adults.[21] NLMF was not found for any force metrics, and this was suggested to be the result of the low-intensity (25-30% maximal strength) protocol not being sufficient. Similar to the present study, Zahiri et al. found larger relative decrements for rapid force compared to maximal force production in the unexercised knee extensors following maximal isometric contractions of the dominant leg.[46] Performance fatigue in exercised muscle leads to greater deficits in rapid force compared to maximal force production,[47,48] and the same may be true in the case of NLMF but more research is needed to test this hypothesis. It is particularly interesting that only early (0-100 ms) rapid force was affected by NLMF. Speculatively, this may indicate that NLMF was mediated through the central nervous system,[1] specifically, a possible slowing of initial neural drive[22,23] may have occurred following the walking task. It is also important to note that the modest intensity associated with the walking task should not have caused sufficient metabolite accrual to reduce central nervous system drive via group III/IV afferent feedback,[49] which is an expected mechanism behind NLMF following more intensive exercise.[1] Given the modest level of exertion for the walking task, cognitive factors may have also mediated the effect. It is not clear why only early RFD decreased for both groups. Future research should complement RFD testing with physiological measurements to better understand NLMF and its mechanistic underpinnings.

To the best of our knowledge, this work is the first to examine the influence of age on NLMF. The present work expands upon existing NLMF literature by highlighting its potential relevance for physical function in middle-aged populations. RFD is typically lower in middle-aged women compared to their younger counterparts,[50,51] so an acute reduction could negatively affect physical function.[24] While research on NLMF is centered around performance fatigue of muscle, it would be

worthwhile for future studies to determine if acute functional declines following NLMF in older populations go beyond isolated muscle function. For example, an important discernment would be if upper-body exercise negatively affected walking speed or chair rise ability. Interestingly, young women exhibited an increase in maximal force following the 6-min walk test. The latter finding supports the importance of examining both RFD and maximal force, since they have been shown to exhibit divergent responses to fatiguing exercise.[52] The fast-paced walking task appeared to prime the muscle for maximal force generating capacity, yet the ability to quickly produce force was diminished. RPE was similar between groups, and in line with the threshold for moderate intensity.[43] The modest intensity associated with the fast-paced walking task was the most likely reason for the lack of an age effect, particularly given that age-related reductions in muscle endurance and maximal oxygen consumption are relatively moderate in mid-life.[53] Recent work demonstrated similar tissue oxygen utilization of lower limb musculature in young and middle-aged women during fast-paced walking indicating the unlikelihood of difference in peripheral fatigue.[54] Future work on NLMF should consider including older adults given the greater performance fatigue response in this population compared to young adults, particularly following dynamic exercise.[25] There are meaningful physical function implications if older adults demonstrate greater reductions in muscle function resulting from NLMF. Additionally, as age-related differences for fatigue in a previously exercised muscle have been well studied, a growing body of evidence on the effect of age on NLMF would enhance perspective and improve the global understanding of fatigue.

There are several limitations associated with the current study. The sample size is relatively small given the between-subjects design, which likely resulted in underpowered analyses. However, the rigor associated with the inclusion and exclusion criteria and strategies to minimize differences for endogenous hormones between groups is noteworthy and should have minimized variability between groups. The lack of a control group was another limitation; thus, it was not determined that changes in muscle function were greater than the expected error. However, the practice afforded during the familiarization visit should have diminished any practice effects and variability. Another limitation was the 3-min delay between the walking task and handgrip testing, because of travel and set up time, which likely diminished the NLMF response. Nonetheless, it is potentially more meaningful that NLMF was present 3-min following exercise which is similar to previous findings.[46] Finally, although body fat percentage is only a descriptor in the present study, we acknowledge that by not controlling hydration status there is additional error in this measurement.

The present study expands upon previous research by examining NLMF in women and through an age-related comparison with middle-aged women. Additionally, this work used fast-paced walking to better understand NLMF following practical, modest exertion more typically associated with acts of daily living. Early rapid force capacity during handgrip testing was reduced similarly between age groups, whereas neither later rapid force nor maximal force outcomes were decreased. Perceived exertion was similar between young and middle-aged likely contributing to the lack of an age difference. While the reason for the preferential reduction in early rapid force is unclear, this finding underscores the need for future NLMF research to supplement standard maximal strength tests with rapid force metrics. Additionally, given the relevance of rapid force production for physical function,[24] this work alludes to the importance of future research examining older populations who may be more prone to exhibit NLMF and vulnerable to declines in physical function.

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Conflicts of interest

The authors certify that there is no conflict of interest with any financial organization regarding the material discussed in the manuscript.

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References

1. Halperin I, Chapman DW, Behm DG. Non-local muscle fatigue: effects and possible mechanisms. Eur *J Appl Physiol.* 2015;115(10):2031-48. https://doi.org/10.1007/s00421-015-3249-y

2. Amiri E, Gharakhanlou R, Rajabi H, Giboin L-s, Rezasoltani Z, Azma K. Non-local muscle fatigue is mediated at spinal and supraspinal levels. *Exp Brain Res.* 2022;240(6):1887-1897. https://doi.org/10.1007/s00221-022-06364-0

3. Sidhu SK, Weavil JC, Venturelli M, et al. Spinal μ-opioid receptor-sensitive lower limb muscle afferents determine corticospinal responsiveness and promote central fatigue in upper limb muscle. *J Physiol.* 2014;592(22):5011-24. https://doi.org/10.1113/jphysiol.2014.275438

4. Amann M, Venturelli M, Ives SJ, et al. Peripheral fatigue limits endurance exercise via a sensory feedback-mediated reduction in spinal motoneuronal output. *J Appl Physiol.* 2013;115(3):355-364. https://doi.org/10.1152/japplphysiol.00049.2013

5. Duffett CA, Wiseman SA, Punjabi A, Power KE, Behm DG. Contralateral muscle fatigue from slow, isokinetic contractions is not velocity-specific. *The Journal of Sport and Exercise Science.* 2022;6(2):65-78. https://doi.org/10.36905/jses.2022.02.01

6. Kennedy A, Hug F, Sveistrup H, Guével A. Fatiguing handgrip exercise alters maximal force-generating capacity of plantar-flexors. Eur *J Appl Physiol.* 2013;113(3):559-66. https://doi.org/10.1007/s00421-012-2462-1

7. Kawamoto JE, Aboodarda SJ, Behm DG. Effect of differing intensities of fatiguing dynamic contractions on contralateral homologous muscle performance. *J Sports Sci Med.* 2014;13(4):836-45.

8. Behm DG, Alizadeh S, Hadjizedah Anvar S, et al. Non-local muscle fatigue effects on muscle strength, power, and endurance in healthy individuals: A systematic review with meta-analysis. *Sports Med.* 2021;51:1893-1907. https://doi.org/10.31236/osf.io/w7x3v

9. Martin PG, Rattey J. Central fatigue explains sex differences in muscle fatigue and contralateral cross-over effects of maximal contractions. *Pflügers Archiv-European Journal of Physiology.* 2007;454(6):957-969. https://doi.org/10.1007/s00424-007-0243-1

10. Ye X, Beck TW, Wages NP, Carr JC. Sex comparisons of non-local muscle fatigue in human elbow flexors and knee extensors. *J Musculoskelet Neuron Interact.* 2018;18(1):92. https://doi.org/29504584

11. Benitez B, Kwak M, Succi PJ, Weir JP, Bergstrom HC. Unilaterally induced quadriceps fatigue during sustained submaximal isometric exercise does not alter contralateral leg extensor performance. *Journal of Functional Morphology and Kinesiology.* 2023;8(2):85. https://doi.org/10.3390/jfmk8020085

12. Doix AC, Lefèvre F, Colson SS. Time course of the cross-over effect of fatigue on the contralateral muscle after unilateral exercise. *PLoS One.* 2013;8(5):e64910. https://doi.org/10.1371/journal.pone.0064910

13. Rasmussen P, Nielsen J, Overgaard M, et al. Reduced muscle activation during exercise related to brain oxygenation and metabolism in humans. *J Physiol.* 2010;588(Pt 11):1985-95. https://doi.org/10.1113/jphysiol.2009.186767

14. Bouhlel E, Chelly MS, Gmada N, Tabka Z, Shephard R. Effect of a prior force-velocity test performed with legs on subsequent peak power output measured with arms or vice versa. *J Strength Cond Res.* 2010;24(4):992-8. https://doi.org/10.1519/JSC.0b013e3181cb2499

15. Post M, Bayrak S, Kernell D, Zijdewind I. Contralateral muscle activity and fatigue in the human first dorsal interosseous muscle. *J Appl Physiol (1985).* 2008;105(1):70-82. https://doi.org/10.1152/japplphysiol.01298.2007

16. Arora S, Budden S, Byrne JM, Behm DG. Effect of unilateral knee extensor fatigue on force and balance of the contralateral limb. Eur *J Appl Physiol.* 2015;115(10):2177-87. https://doi.org/10.1007/s00421-015-3198-5

17. Paillard T, Chaubet V, Maitre J, Dumitrescu M, Borel L. Disturbance of contralateral unipedal postural control after stimulated and voluntary contractions of the ipsilateral limb. *Neuroscience research.* 2010;68(4):301-306. https://doi.org/10.1016/j.neures.2010.08.004

18. Millet GY, Martin V, Lattier G, Ballay Y. Mechanisms contributing to knee extensor strength loss after prolonged running exercise. *J Appl Physiol.* 2003;94(1):193-198. https://doi.org/10.1152/japplphysiol.00600.2002

19. Ross EZ, Middleton N, Shave R, George K, Nowicky A. Corticomotor excitability contributes to neuromuscular fatigue following marathon running in man. *Exp Physiol.* 2007;92(2):417-26. https://doi.org/10.1113/expphysiol.2006.035972

20. Decorte N, Lafaix PA, Millet GY, Wuyam B, Verges S. Central and peripheral fatigue kinetics during exhaustive constant-load cycling. *Scand J Med Sci Sports.* 2012;22(3):381-391. https://doi.org/10.1111/j.1600-0838.2010.01167.x

21. Miller W, Jeon S, Ye X. An examination of acute cross-over effects following unilateral low intensity concentric and eccentric exercise. *Sports Medicine and Health Science.* 2020;2(3):141-152. https://doi.org/10.1016/j.smhs.2020.08.002

22. Del Vecchio A, Negro F, Holobar A, et al. You are as fast as your motor neurons: speed of recruitment and maximal discharge of motor neurons determine the maximal rate of force development in humans. *J Physiol.* 2019;597(9):2445-2456. https://doi.org/10.1113/JP277396

23. Klass M, Baudry S, Duchateau J. Age-related decline in rate of torque development is accompanied by lower maximal motor unit discharge frequency during fast contractions. *J Appl Physiol.* 2008;104(3):739-746.

24. Hester GM, Ha PL, Dalton BE, et al. Rate of Force Development as a Predictor of Mobility in Community-dwelling Older Adults. *J Geriatr Phys Ther.* 2021;44(2):74-81. https://doi.org/10.1519/JPT.0000000000000258

25. Rozand V, Senefeld JW, Hassanlouei H, Hunter SK. Voluntary activation and variability during maximal dynamic contractions with aging. Eur *J Appl Physiol.* 2017;117:2493-2507. https://doi.org/10.1007/s00421-017-3737-3

26. Callahan DM, Kent-Braun JA. Effect of old age on human skeletal muscle force-velocity and fatigue properties. *J Appl Physiol.* 2011;111(5):1345-1352. https://doi.org/10.1152/japplphysiol.00367.2011

27. Yoon T, Schlinder-Delap B, Hunter SK. Fatigability and recovery of arm muscles with advanced age for dynamic and isometric contractions. *Exp Gerontol.* 2013;48(2):259-68. https://doi.org/10.1016/j.exger.2012.10.006

28. Klass M, Baudry S, Duchateau J. Aging does not affect voluntary activation of the ankle dorsiflexors during isometric, concentric, and eccentric contractions. *J Appl Physiol.* 2005;99(1):31-38. https://doi.org/10.1152/japplphysiol.01426.2004

29. Christie A, Snook EM, Kent-Braun JA. Systematic review and meta-analysis of skeletal muscle fatigue in old age. *Medicine and science in sports and exercise.* 2011;43(4):568. https://doi.org/10.1249/MSS.0b013e3181f9b1c4

30. Morrison S, Colberg SR, Parson HK, et al. Walking-Induced Fatigue Leads to Increased Falls Risk in Older Adults. *J Am Med Dir Assoc.* 2016;17(5):402-9. https://doi.org/10.1016/j.jamda.2015.12.013

31. D'Emanuele S, Maffiuletti NA, Tarperi C, Rainoldi A, Schena F, Boccia G. Rate of force development as an indicator of neuromuscular fatigue: a scoping review. *Frontiers in human neuroscience.* 2021;15:701916. https://doi.org/10.3389/fnhum.2021.701916

32. Boccia G, Dardanello D, Tarperi C, et al. Fatigue-induced dissociation between rate of force development and maximal force across repeated rapid contractions. *Human Movement Science.* 2017;54:267-275. https://doi.org/10.1016/j.humov.2017.05.016

33. Piasecki J, Škarabot J, Spillane P, Piasecki M, Ansdell P. Sex differences in neuromuscular aging: the role of sex hormones. *Exerc Sport Sci Rev.* 2024;52(2):54-62. https://doi.org/10.1249/JES.0000000000000335

34. Smith SS, Woodward DJ, Chapin JK. Sex steroids modulate motor-correlated increases in cerebellar discharge. *Brain Res.* 1989;476(2):307-316. https://doi.org/10.1016/0006-8993(89)91251-1

35. Kilpi F, Soares AG, Clayton GL, et al. Changes in women's physical function in mid-life by reproductive age and hormones: a longitudinal study. *BMC Womens Health.* 2022;22(1):473. https://doi.org/10.1186/s12905-022-02070-9

36. Kurina LM, Gulati M, Everson-Rose SA, et al. The effect of menopause on grip and pinch strength: results from the Chicago, Illinois, site of the Study of Women's Health Across the Nation. *Am J Epidemiol.* 2004;160(5):484-491. https://doi.org/10.1093/aje/kwh244

37. Craig CL, Marshall AL, Sjöström M, et al. International physical activity questionnaire: 12-country reliability and validity. *Med Sci Sports Exerc.* 2003;35(8):1381-1395. https://doi.org/10.1249/01.MSS.0000078924.61453.FB

38. Navalta JW, Stone WJ. Ethical issues relating to scientific discovery in exercise science. *International journal of exercise science.* 2020;12(1):1. https://doi.org/10.70252/EYCD6235

39. Bryant AL, Clark RA, Bartold S, et al. Effects of estrogen on the mechanical behavior of the human Achilles tendon in vivo. *J Appl Physiol.* 2008;105(4):1035-1043. https://doi.org/10.1152/japplphysiol.01281.2007

40. Elliott KJ, Cable NT, Reilly T. Does oral contraceptive use affect maximum force production in women? Br J *Sports Med.* 2005;39(1):15-9. https://doi.org/10.1136/bjsm.2003.009886

41. Enright PL. The six-minute walk test. *Respiratory care.* 2003;48(8):783-785.

42. Yu CY, Lin HC. Exploring Factors Regarding Transit-related Walking and Walking Duration. *Journal of Physical Activity & Health.* 2016;13(11):1220-1229. https://doi.org/10.1123/jpah.2015-0667

43. Borg G. Borg's perceived exertion and pain scales. *Human kinetics*; 1998.

44. Thompson BJ. Influence of signal filtering and sample rate on isometric torque–time parameters using a traditional isokinetic dynamometer. *J Biomech.* 2019;83:235-242. https://doi.org/10.1016/j.jbiomech.2018.12.006

45. Field A. Discovering statistics using IBM SPSS statistics. 3rd ed. Sage; 2009.

46. Zahiri A, Goudini R, Alizadeh S, et al. The duration of non-local muscle fatigue effects. *Journal of Sports Science & Medicine.* 2024;23(2):425. https://doi.org/10.52082/jssm.2024.425

47. Buckthorpe M, Pain MT, Folland JP. Central fatigue contributes to the greater reductions in explosive than maximal strength with high-intensity fatigue. *Experimental Physiology.* 2014;99(7):964-973. https://doi.org/10.1113/expphysiol.2013.075614

48. Minshull C, James L. The effects of hypohydration and fatigue on neuromuscular activation performance. *Appl Physiol Nutr Metab.* 2013;38(999):21-26. https://doi.org/10.1139/apnm-2012-0189

49. Sidhu SK, Weavil JC, Mangum TS, et al. Group III/IV locomotor muscle afferents alter motor cortical and corticospinal excitability and promote central fatigue during cycling exercise. *Clinical Neurophysiology.* 2017;128(1):44-55. https://doi.org/10.1016/j.clinph.2016.10.008

50. Libardi CA, Souza TMF, Conceição MS, et al. Electromechanical delay of the knee extensor muscles: comparison among young, middle-age and older individuals. *Clin Physiol Funct Imaging.* 2015;35(4):245-249. https://doi.org/10.1111/cpf.12157

51. Phillips KC, Noh B, Gage M, Yoon T. Neural and muscular alterations of the plantar flexors in middle-aged women. *Exp Gerontol.* 2022;159:111674. https://doi.org/10.1016/j.exger.2021.111674

52. Buckthorpe M, Pain MTG, Folland JP. Central fatigue contributes to the greater reductions in explosive than maximal strength with high-intensity fatigue. *Experimental Physiology.* 2014;99(7):964-973. https://doi.org/10.1113/expphysiol.2013.075614

53. Clarike DH, Hunt MQ, Dotson CO. Muscular strength and endurance as a function of age and activity level. *Research quarterly for exercise and sport.* 1992;63(3):302-310. https://doi.org/10.1080/02701367.1992.10608746

54. Landers-Ramos RQ, Merriman K, Chartier GL, Parks J, Park H, Knuth ND. Comparison of skeletal muscle oxidative function in young, middle-aged, and older males and females with similar physical activity levels. *J Appl Physiol.* 2024;136(3):618-629. https://doi.org/10.1152/japplphysiol.00545.2023