Trade-Off Between Maximal Power Output and Fatigue Resistance of the Knee Extensors for Older Men

Ryota Akagi,1 Yuta Nomura,2 Chiho Kawashima,1 Mari Ito,2 Kosuke Oba,1 Yuma Tsuchiya,2 Geoffrey A. Power,3 and Kosuke Hirata4

1Department of Bioscience and Engineering, College of Systems Engineering and Science, Shibaura Institute of Technology, Saitama-shi, Japan; 2Graduate School of Engineering and Science, Shibaura Institute of Technology, Saitama-shi, Japan; 3Department of Human Health and Nutritional Sciences, College of Biological Science, University of Guelph, Guelph, ON, Canada; 4Faculty of Sport Sciences, Waseda University, Tokorozawa-shi, Japan

This study investigated associations of fatigue resistance determined by an exercise-induced decrease in neuromuscular power with prefatigue neuromuscular strength and power of the knee extensors in 31 older men (65–88 years). A fatigue task consisted of 50 consecutive maximal effort isotonic knee extensions (resistance: 20% of prefatigue isometric maximal voluntary contraction torque) over a 70° range of motion. The average of the peak power values calculated from the 46th to 50th contractions during the fatigue task was normalized to the prefatigue peak power value, which was defined as neuromuscular fatigue resistance. Neuromuscular fatigue resistance was negatively associated with prefatigue maximal power output ($r = −0.530$) but not with prefatigue maximal voluntary contraction torque ($r = −0.252$). This result highlights a trade-off between prefatigue maximal power output and neuromuscular fatigue resistance, implying that an improvement in maximal power output might have a negative impact on neuromuscular fatigue resistance.

Keywords: isometric contraction, isotonic contraction, muscle shear modulus, interpolated twitch technique

Natural adult aging is associated with decreased neuromuscular fatigue resistance, evidenced by a decrease in neuromuscular power/strength, across a variety of physical activity levels (Dalton et al., 2010; Sundberg, Kuplic, et al., 2018; Theou et al., 2008) and muscle groups (Dalton et al., 2015, 2010; Senefeld et al., 2017; Sundberg, Kuplic, et al., 2018; Wallace et al., 2016) compared with young adults. This fatiguability is amplified when neuromuscular fatigue resistance is evaluated using muscle power, not strength, as the criterion measure. This age-related decreased fatiguability has negative implications on activities of daily living, such as standing balance and walking (Senefeld et al., 2017), and is associated with frailty (Theou et al., 2008). Therefore, understanding the neuromuscular determinants of fatigue resistance of aged muscles assessed via power, especially the knee extensors (KE), is essential to identify ways to improve and maintain a high quality of life for older adults. On the other hand, muscle power declines at a faster rate than muscle strength (Izquierdo et al., 1999; Reid & Fielding, 2012; Reid et al., 2014) over the lifespan; this is concerning as age-related reductions in muscle power output have a greater implication than weakness (i.e., strength) on performance of daily tasks and functional independence (Evans, 2000). In other words, both maximal muscle power output and neuromuscular fatigue resistance assessed with muscle power as the criterion measure are important in predicting functional capacity for older adults.

When compared with young adults, prefatigue maximal muscle power output and neuromuscular fatigue resistance for older individuals are lower under isokinetic conditions (Dalton et al., 2010; Sundberg, Kuplic, et al., 2018). Sundberg, Hunter, et al. (2018) showed that the age-related loss in muscle power is primarily determined by the atrophy of fast fibers, but the mechanism responsible for the decreased neuromuscular fatigue resistance with aging is unresolved. If this unexplained mechanism for the age-related difference in neuromuscular fatigue resistance applies to individual differences in older adults, then it is natural to assume that those with higher prefatigue power outputs would also have higher neuromuscular fatigue resistance. Neuromuscular fatigue resistance is highly task dependent (Enoka, 1995), and for dynamic contractions, the findings regarding age-related differences in neuromuscular fatigue resistance differ between isokinetic and isometric conditions (Dalton et al., 2015). Everyday movements involve ballistic sinusoidal changes in velocity with constant loads (i.e., isokinetic conditions) rather than constant velocity (i.e., isometric conditions) (Cairns et al., 2005), and measuring neuromuscular fatigue under isometric conditions is considered to be more relevant to physical performance during activities of daily living (McNeil & Rice, 2007). Therefore, the association between pre-fatigue maximal power output and neuromuscular fatigue resistance for older adults needs to be investigated under isometric conditions to optimize training and/or rehabilitation regimens.

The current study determined maximal power output and neuromuscular fatigue resistance of the KE under isometric conditions (maximal effort isometric “power” contractions) along with various indices of fatigue, such as maximal voluntary contraction (MVC) torque, evoked torque, surface electromyography (EMG), and muscle stiffness evaluated by muscle shear modulus (e.g., Akagi et al.,...
2019), before, during, and after a fatigue task for older men. Furthermore, to better understand the association between prefatigue maximal power output and neuromuscular fatigue resistance, individual differences in the relationship between power and reciprocals of the number of contractions during the fatiguing task were investigated with reference to previously reported power–duration relationships (Burnley & Jones, 2018; Neder et al., 2000; Poole et al., 2016). It was hypothesized that older people with a higher prefatigue power output have greater neuromuscular fatigue resistance.

Materials and Methods

Sample Size Calculation and Participants

The main outcome of this study was an association between prefatigue peak power and neuromuscular fatigue resistance under isotonic conditions. Hence, an a priori sample size estimation was performed for a correlation calculation using the G*Power software package (version 3.1.9.4, Kiel University) before recruiting participants. The input parameters were as follows: statistical test = correlation: point biserial model; tail(s) = 2; effect size |ρ| = 0.5; α err prob = .05; and power (1 – β err prob) = 0.80. As a result, the sample size was calculated to be 26. In consideration of the possibility of dropouts, we recruited a slightly larger number of participants, and 33 healthy older men (mean ± SD; age: 74 ± 6 years [range: 65–88 years], height: 166.0 ± 6.5 cm [range: 150.3–176.5 cm], body mass: 65.5 ± 9.7 kg [range: 48.3–86.1 kg]) were recruited to participate in this study. The participants were free of cardiovascular and neuromuscular diseases, were functionally independent in daily life, were recreationally active, and did not perform any specific training regarding knee extension. None of the participants had self-reported knee joint pain at the time of experiment or previous knee surgery. This study was approved by the Ethics Committee of the Shibaura Institute of Technology and conducted in accordance with the Declaration of Helsinki. The participants were informed of the purpose and potential risks of the study and provided written informed consent before participation.

Experimental Procedures

A fatigue task consisting of 50 consecutive maximal effort isotonic knee extensions (resistance: 20% of prefatigue isometric MVC torque; a 1-s rest interval between each contraction) over a 70° range of motion (ROM; 110°–40° of knee joint angle) with the hip at 80° (both anatomical positions = 0°) was performed. Before and after the fatigue task (Pre and Post), isometric MVC torque; potentiated twitch torque; voluntary activation (VA%); root mean square values of the EMG signals (RMS-EMGs) of the rectus femoris (RF), vastus lateralis (VL), vastus medialis (VM), and biceps femoris (BF) muscle; and muscle shear modulus of the RF and VL were determined. Isotonic peak power (resistance: 20% of prefatigue isometric MVC torque) was measured at Pre and during the fatigue task. In a previous study (Dalton et al., 2010), participants performed 50 maximal dynamic plantar flexions as a fatigue task, and an average of power of each dynamic contraction normalized to the baseline value was calculated over every five contractions. With reference to this previous study, the average of the peak power values calculated from the 46th to 50th contractions (i.e., the last five contractions) during the fatigue task was normalized to the prefatigue value of peak power to assess neuromuscular fatigue resistance. Here, angular velocity was calculated by differentiating angle, and peak power was calculated using the product of torque and angular velocity. At Pre and the 46th–50th contractions, RMS-EMGs of the RF, VL, VM, and BF were also evaluated. Furthermore, a relationship between power and number of contractions was investigated for each participant with reference to previously reported power–duration relationships (Burnley & Jones, 2018; Neder et al., 2000; Poole et al., 2016). The torque and angle data were obtained using a dynamometer (CON-TREX MJ, Physiomed), and the EMG was assessed using a standard EMG system (Bagnoli 8 EMG System, DELSYS). The torque, angle, and EMG data were recorded at a sampling frequency of 2000 Hz on a personal computer using LabChart software (version 8.1.16, ADInstruments) after the A/D conversion (PowerLab16/35, ADInstruments). Measurements were performed on the right thigh, and the temperature of the experimental room was kept constant at around 23 °C throughout the measurements. Strong verbal encouragement was provided to the participants during the isometric and isotonic measurements and the fatigue task.

Measurement Positions of Muscle Shear Modulus and EMG Activities

The thigh length from the greater trochanter to the popliteal crease of the participants was first measured with a steal tape in 0.5-cm increments while they were standing upright to determine the measurement positions of muscle shear modulus and EMG activities. At that time, marks were made at the distal 20% (for the VM EMG activity), 50% (for the RF and BF EMG activities and the VL shear modulus), and 70% (for the VL EMG activity and the RF shear modulus) of the thigh length.

The participants were then placed in a prone position on a bed. The center of the width in the mediolateral direction and fascicle longitudinal direction of the BF at the distal 50% of the thigh length were confirmed using an ultrasound apparatus (ACUSON S3000, Siemens Medical Solutions) coupled with a linear transducer array (9L4 Transducer, 4–9 MHz, Siemens Medical Solutions). A pre-amplified bipolar active surface EMG electrode (electrode shape: parallel bar, size: 1 mm width × 10 mm length, interelectrode distance: 10 mm; DE-2.1, DELSYS) with band-pass filtering between 20 and 450 Hz was placed in the confirmed location after preparing the skin by shaving, abrasion with sandpaper, and cleaning with alcohol.

Afterward, the participants sat on a reclining seat of the dynamometer with the hip at 80° and the knee at 90° flexion. The pelvis and torso were secured to the reclining seat and dynamometer with nonelastic straps and/or a seat belt. Care was taken to adjust the centers of rotation of the knee joint and dynamometer. An ankle adapter attached to a lever arm was positioned slightly proximal to the lateral malleolus with the nonelastic strap. In all measurements except isotopic peak power measurements, the participants’ posture was as described above. To determine the measurement sites of muscle shear modulus, the centers of the widths in the mediolateral direction of the RF and VL were confirmed at the distal 70% and 50% of the thigh length, respectively, using the ultrasound apparatus. Then, the preamplified bipolar active surface EMG electrodes were also placed on the RF, VL, and VM at the distal 50%, 70%, and 20% of the thigh length, respectively. A reference electrode was placed over the lateral malleolus.

Measurements of Muscle Shear Modulus at Pre

The ultrasonic apparatus coupled with the linear transducer array was used to quantify muscle shear modulus. The linear transducer...
array was longitudinally placed at the aforementioned sites with water-soluble transmission gel to measure the shear moduli of RF and VL in a random order. During the measurement, to avoid influencing the values of muscle shear moduli, the examiner was careful not to apply pressure on the target muscle. The examiner obtained an elastography image on a scale from blue (soft) to red (hard) depending on the magnitude of shear wave propagation speed. Before storing, the elastography image was investigated to determine whether the shear wave was sufficient in quality to yield accurate measurements using the system of the ultrasonic apparatus; this system displayed color-coded images on a scale from green (good) to orange (bad). When yellow-to-orange pixels occupied ≤25% area of a color-coded image within the region of interest (ROI) of a color map, we judged that the quality of the image was acceptable. Until the three elastography images of each muscle thought to have sufficient quality were obtained, the measurements were repeated.

Elastographic images were exported in DICOM format from the ultrasonic apparatus. The ROI on each color map was made as large as possible while excluding nontarget tissues (e.g., subcutaneous adipose tissues, aponeuroses, nontarget muscles, etc.) using image processing software (ImageJ 1.51j8, National Institutes of Health). The average value of the shear wave propagation speed over the ROI was calculated for each image using an analysis software written in MATLAB (MATLAB R2018a, MathWorks; Hirata et al., 2020). This software can convert the red–green–blue values of each pixel within the ROI into the values of shear wave propagation speed according to the color scale of the elastographic image. Shear modulus of a muscle was calculated as the product of muscle density and shear wave propagation speed squared (Akagi et al., 2017; Nordez & Hug, 2010). In the present study, the muscle density was assumed to be 1,084 kg/m³, which was the mean of the two values reported in a previous study (Ward & Lieber, 2005). For each muscle, the average of the values calculated from three images were used for further analyses. The coefficient of variation and intraclass correlation coefficient for the measured values of shear wave propagation speed were calculated to evaluate the accuracy of the examiner. The coefficients of variation and intraclass correlation coefficients (type 1,3) for the three values (31 participants [the reason for the decrease of two participants is as described later] × 2 time points [Pre and Post]) were 2.3 ± 1.9% and 0.984 (p < .001) for RF and 2.1 ± 2.2% and 0.935 (p < .001) for VL, respectively.

**Measurements of Peak-to-Peak Compound Muscle Action Potential Amplitude (M\text{max}) at Pre**

A constant-current variable voltage stimulator (DS7AH, Digitimer Ltd.) with a controller (SEN-3401, Nihon Kohden) was used to determine M\text{max} of the RF, VL, and VM. To percutaneously stimulate the femoral nerve with rectangular pulses of 200 μs, a cathode (2 × 2 cm) and anode (4 × 5 cm) were placed in the femoral triangle and midway between the superior aspect of the greater trochanter and inferior border of the iliac crest, respectively. The stimulus intensity was increased from 20 mA in increments of 10 mA until a plateau in the twitch torque was reached, and supramaximal stimulus intensity was set at the electrical current calculated by multiplying the stimulus intensity by 1.4 (Akagi, Hinks, Davidson, & Power, 2020; Akagi, Hinks, & Power, 2020). Resting-evoked twitch responses were obtained twice every 10 s to determine the M\text{max} of the RF, VL, and VM, and the higher value was adopted for each muscle.

**Isometric Measurements at Pre**

After performing warm-up procedures consisting of submaximal contractions, the peak torque during isometric MVC of the KE (for 3 s) was assessed over two contraction attempts with a 1-min rest interval. If the difference between the two values of peak torque was >10% of the higher torque, then additional contractions were performed until the difference between the highest and second highest values was less than 10% of the highest value; 1 min of rest was allowed between contractions. When measuring the peak torque during isometric MVC of the KE, two supramaximal twitch stimulations were interpolated approximately 2 and 3 s after the beginning and end of contraction, respectively, to determine potentiated twitch torque and VA%. The following formula was used to calculate VA%: \[1 – (\text{superimposed twitch torque/potenti- ated resting twitch torque}) \times 100 = \text{VA}%.\] In addition, during the isometric MVC of the KE, the RMS-EMGs of the RF, VL, VM, and BF were evaluated over a 0.5-s period around the peak torque. The highest value of peak torque was determined as the isometric MVC torque, and the values of potentiated twitch torque, VA%, and RMS-EMGs of the RF, VL, VM and BF in the selected task, in which the highest value of peak torque was observed, were used for further analyses. Here, RMS-EMGs of the RF, VL, and VM were normalized by M\text{max}. Furthermore, the peak torque during isometric MVC of the knee flexors was determined twice with a 1-min interval. The RMS-EMG of the BF in the selected task, in which the highest value of isometric MVC torque of the knee flexors was observed, was assessed over a 500-ms period around the peak torque and was used to normalize RMS-EMG of the BF during MVC of the KE. When analyzing the isometric MVC torque, potentiated twitch torque, and VA% offline, the torque data were low-pass filtered at 500 Hz.

**Isotonic Measurements at Pre**

Maximal effort isotonic contractions of the KE with a resistance (i.e., load) set to 20% of isometric MVC torque were repeated three times every 3–4 s from a knee joint angle of 110° to 40°. The lever arm with the ankle adapter was automatically returned to its initial position (i.e., 110° knee joint angle) over a period of 1 s as soon as it reached the end of the ROM. During this, the participants were asked to be fully relaxed. The highest value of three measurements of peak power was used as the prefatigue value of peak power. The dynamometer (CON-TREX MJ, Physiomed) generated an additional breaking force as the lever arm approached the end of the ROM, which could result in torque and power spikes (Figure 1). Therefore, we decided to evaluate the first peak value of power. In addition, RMS-EMGs of the RF, VL, VM, and BF in the task with the highest peak power were assessed over a time interval of 0–100 ms from the onset of movement of the lever arm and were normalized in the same way as under isometric conditions. When analyzing isotonic peak power offline, the torque and angular velocity data were low-pass filtered at 20 Hz.

**Fatigue Task**

Three minutes after the peak power measurement was completed, the fatigue task was started. As described earlier, the lever arm with ankle adapter was automatically returned to its initial position (i.e., 110° knee joint angle) over a period of 1 s as soon as it reached the end of the ROM. Immediately thereafter, the participants performed the knee extension again. That is, they performed 50 consecutive maximal effort isotonic knee extensions with a 1-s rest
interval. The average of the peak power values calculated from the 46th–50th contractions during the fatigue task was determined as the post value and was normalized to the prefatigue value of peak power for assessing neuromuscular fatigue resistance. Similarly, the values of RMS-EMGs for the 46th to 50th contractions during the fatigue task were averaged and used as the Post value. If the participants could not extend their knee to the end of the ROM, the examiner immediately completed the ROM on behalf of the participants. In such cases, the rest time between contractions was longer, and the peak power values in the immediately following trials were expected to be easily recoverable. Hence, the values of peak power and RMS-EMGs in the following trial were excluded from the analysis.

Previous studies (Burnley & Jones, 2018; Neder et al., 2000; Poole et al., 2016) have reported that the hyperbolic power–duration relationship ($y$-axis: power; $x$-axis: time) can be transformed into a linear relationship ($y$-axis: power, $x$-axis: 1/time). Here, the slope and the intercept are considered to be the curvature constant (fatigability constant) and the critical power (fatigue threshold) of the power–duration relationship, respectively (Poole et al., 2016). If we apply the power–duration relationship to the relationship between power ($y$-axis) and number of contractions ($x$-axis) obtained in the present study, it is reasonable to assume that those individuals with lower neuromuscular fatigue resistance had higher slopes (curvature constant) and/or lower intercepts (critical power). In fact, those individuals with higher curvature constant had a lower fatigue resistance in a previous study (Broxterman et al., 2015). Hence, the following procedure was used to linearize the relationship between power and number of contractions and then calculate the slope and intercept of the regression line for each participant. (a) The average values of peak power in the first–fifth, sixth–10th, 11th–15th, 16th–20th, 21st–25th, 26th–30th, 31st–35th, 36th–40th, 41st–45th, and 46th–50th contractions were calculated as the representative values of peak power in the fifth, 10th, 15th, 20th, 25th, 30th, 35th, 40th, 45th, and 50th contractions, respectively. (b) These values were then normalized to the prefatigue peak power and expressed as a percentage. (c) The reciprocals of number of contractions (i.e., 1/5, 1/10, 1/15, 1/20, 1/25, 1/30, 1/35, 1/40, 1/45, and 1/50) were calculated. (d) The normalized values of peak power ($y$-axis) and the reciprocals of number of contractions ($x$-axis) were plotted with the prefatigue values (here, considered as follows: $[x, y] = [1, 100]$). (e) The slope and intercept of the linear regression of these plots were then calculated, respectively.

### Isometric Measurements and Measurements of Muscle Shear Modulus at Post

The measurements of isometric MVC torque, potentiated twitch torque, VA%, and RMS-EMGs of each muscle were started 30 s after the end of the fatigue task to allow for changing form the isotonic to isometric mode of the dynamometer. Afterward, the RF and VL shear moduli were determined three times, respectively, in a random order.

### Statistical Analyses

Two older men were excluded from analysis for failure to perform the voluntary efforts maximally. Therefore, the data of 31 participants were included in the present study (mean ± SD; age: 73 ± 6 years [range: 65–88 years], height: 166.1 ± 6.7 cm [range: 150.3–176.5 cm], body mass: 65.9 ± 9.9 kg [range: 48.3–86.1 kg]).
Differences in isotonic peak power, isometric MVC torque, potentiated twitch torque, VA%, and normalized RMS-EMG of the BF between Pre and Post were examined using a paired t test. To investigate changes in shear moduli of the RF and VL and normalized RMS-EMGs of the RF, VL, and VM induced by the fatigue task, two-way repeated-measures analysis of variance with two within-group factors (time point [Pre, Post], muscle [RF and VL for shear moduli; RF, VL, and VM for RMS-EMGs]) was used. Here, we did not check for a main effect of muscle because we were not interested in comparisons between the muscles. To avoid misrepresentation of null-hypothesis significance testing, Cohen’s $d$ was also calculated as an index of the effect size when comparing the same variable between Pre and Post. Associations between the prefatigue values of isotonic peak power or isometric MVC torque and neuromuscular fatigue resistance were investigated using Pearson’s correlation coefficient. For the relationship between power and reciprocals of number of contractions, associations of the slope (the curvature constant) and the intercept (the critical power) with prefatigue peak power and neuromuscular fatigue resistance were investigated using Pearson’s correlation coefficient.

The data of many variables were found not to be normally distributed by the Shapiro–Wilk test (Supplementary Table S1 [available online]). Therefore, all data were log transformed, and the aforementioned statistical analyses were conducted using them.

Statistical significance was set to $p < .05$. The value of $d$ was $d < 0.20$ for trivial, $0.20 \leq d < 0.50$ for small, $0.50 \leq d < 0.80$ for medium, and $0.80 \leq d$ for large effects (Cohen, 1988). Statistical analyses were performed using statistical analysis software (SPSS, version 25.0, IBM). For ease of interpretation, data in the text and figures are presented as means ± SDs of raw data.

**Results**

The average peak power for each of the five contractions during the fatigue task (normalized to the prefatigue peak power) is shown in Supplementary Figure S1 (available online). Following the fatigue task, isotonic peak power, isometric MVC torque, and potentiated twitch torque were reduced by 50%, 14%, and 25%, respectively ($p < .001$), with large effects ($d = 2.68, 0.88, \text{and} 1.43$), whereas there was no significant difference in VA% ($p = .953, d = 0.01$) (Figure 2). Normalized RMS-EMGs of the RF, VL, and VM had no Time point × Muscle interaction or main effect of time point both during isometric (Figure 3a–3c; interaction: $p = .753$, main effect: $p = .327$, $d = 0.04–0.11$) and isotonic (Figure 4a–4c; interaction: $p = .729$, main effect: $p = .156$, $d = 0.07–0.21$) contractions. Regarding normalized RMS-EMG of the BF, no significant difference between Pre and Post was found both under isometric (Figure 3d; $p = .057$, $d = 0.14$) and isotonic (Figure 4d; $p = .050$, $d = 0.195$) conditions. There was a significant main effect of time.

![Figure 2](image-url) — Isotonic peak power (a), isometric MVC torque (b), potentiated twitch torque (c), and VA% (d) of the knee extensors before and after a fatigue task (Pre and Post; $n = 31$). Black circles and thick solid lines in the vertical directions indicate means and SDs, respectively. Thin dashed lines indicate individual data. The data were log transformed when analyzing and are presented as raw values. MVC = maximal voluntary contraction; VA% = voluntary activation.
point \( (p < .001) \) without a significant time point \( \times \) muscle interaction \( (p = .369) \) for muscle shear moduli, indicating the significant increases in shear moduli of the RF (16\%) and VL (8\%) induced by the fatigue task with small effects \( (d = 0.46 \) and 0.47; Figure 5).

Prefatigue peak power was negatively correlated with neuromuscular fatigue resistance \( (50.3 \pm 11.6\%; \ r = -.530, p = .002; \) Figure 6a). In contrast, prefatigue MVC torque was not related to neuromuscular fatigue resistance \( (r = -.252, p = .172; \) Figure 6b).

Regarding the relationship between power and reciprocals of number of contractions, the slope (the curvature constant) was correlated with prefatigue peak power positively \( (r = .409, p = .022; \) Figure 7a) and neuromuscular fatigue resistance negatively \( (r = -.851, p < .001; \) Figure 7b). The intercept (the critical power) was also correlated with prefatigue peak power negatively \( (r = -.484, p = .006; \) Figure 7c) and neuromuscular fatigue resistance positively \( (r = .801, p < .001; \) Figure 7d).

**Discussion**

In the present study, we show a negative association between prefatigue maximal power output and fatigue resistance of the KE for older men, indicating that those individuals with a higher prefatigue power output have lower fatigue resistance of the KE. This result did not support the hypothesis that older people with a higher prefatigue power output have higher neuromuscular fatigue resistance.

The MVC torque and potentiated twitch torque under isometric conditions and maximal effort peak power under isotonic conditions were all reduced following the fatigue task (Figure 2a–2c). On the other hand, there were no fatigue-induced changes in VA\% (Figure 2d) and normalized RMS-EMGs of each muscle (Figures 3 and 4). Considering that reductions in potentiated twitch torque indicate peripheral fatigue (O’Leary et al., 2017) and declines in RMS-EMGs (Papaioordanidou et al., 2010; Place et al., 2010) and VA\% (Burnley et al., 2012) likely indicate central fatigue, the present results indicate that impairments in neuromuscular function are likely of a peripheral origin. In addition, there were fatigue-induced increases in the RF and VL shear moduli (Figure 5). As the latest review article on peripheral fatigue (Cè et al., 2020) summarized, muscle shear modulus is, indeed, a measure of peripheral fatigue, but there is no consensus on the fatigue-induced change in resting muscle shear modulus. However, resting tension develops when muscles fail to completely relax during fatigue (Gong et al., 2003, 2000), likely resulting in the greater muscle stiffness based on the theoretical model of muscle stiffness (Dresner et al., 2001).
Consequently, it is reasonable to think that the RF and VL were impaired by the fatigue task and stiffened accordingly, thus supporting that the impairments in power output were likely attributed to peripheral rather than central factors.

Neuromuscular fatigue resistance was negatively related to isotonic peak power of the KE (Figure 6a). That is, there was a trade-off between high power output ability and fatigue resistance of the KE such that those individuals with higher prefatigue power output values incurred a greater power loss following the fatigue task. In the present study, the association of the slope of the regression line between power and reciprocals of number of contractions (i.e., the curvature constant) with neuromuscular fatigue resistance (Figure 7b) was found. This result is consistent with a previous finding that those individuals with higher curvature constant had a lower fatigue resistance (Broxterman et al., 2015). Furthermore, those individuals with higher slopes also had higher prefatigue peak power (Figure 7a), and those individuals with higher intercepts (the critical power) had lower prefatigue peak power (Figure 7c) and greater fatigue resistance (Figure 7d). These results for the slope and intercept can explain the aforementioned trade-off between high power output ability and fatigue resistance of the KE. Under severe-intensity exercise, both the curvature constant and critical power are sensitive to the oxygen delivery characterized by the recruitment of low-oxidative Type II fibers and neuronal nitric oxide synthase-controlled increases in blood flow (Poole et al., 2016). The intramuscular pressure developed during each contraction may be relatively higher in the more powerful participants, thus leading to greater occlusion of blood flow to the working muscle group during each contraction (Kent-Braun et al., 2002; Mcphee et al., 2014). Accordingly, the oxygen delivery to the muscle group may have been impaired in the more powerful participants during the fatigue task (Kent-Braun et al., 2002; Lee et al., 2021), worsening their neuromuscular fatigue resistance. Considering that both maximal power output and neuromuscular fatigue resistance assessed under isotonic conditions are higher in young than older adults (Dalton et al., 2015, 2010), however, this mechanism cannot explain the age-related difference in neuromuscular fatigue resistance. Further research will be required to clarify the mechanism.

In contrast to the aforementioned trade-off between prefatigue peak power and neuromuscular fatigue resistance, there was no association between prefatigue MVC torque and neuromuscular fatigue resistance of the KE (Figure 6b). In the present study, neuromuscular fatigue resistance was assessed using the fatigue-induced change in peak power not isometric MVC torque. In addition, power is affected by not only torque but also angular velocity; in fact, some previous studies (Akagi, Hinks, Davidson, & Power, 2020; Cheng & Rice, 2009; Dalton et al., 2010; Krüger

Figure 4 — Normalized RMS-EMGs of the RF (a), VL (b), VM (c), and BF (d) during maximal effort isotonic contraction (resistance: 20% of prefatigue isometric maximal voluntary contraction torque) of the knee extensors before and after a fatigue task (Pre and Post; n = 31). Black circles and thick solid lines in the vertical directions indicate means and SDs, respectively. Thin dashed lines indicate individual data. The data were log transformed when analyzing and are presented as raw values. For the RF, VL, and VM, a two-way repeated-measures analysis of variance was performed, and a time point × muscle interaction and a main effect of time point were not significant. For the BF, a paired t test was performed, and there was no significant difference between Pre and Post. EMG = electromyography; RF = rectus femoris; VL = vastus lateralis; VM = vastus medialis; BF = biceps femoris; RMS-EMGs = root mean square values of the EMG signals.
et al., 2019) have described that fatigue-induced reductions in isometric MVC torque do not entirely reflect fatigue-induced alterations to neuromuscular function, especially as related to dynamic performance. Therefore, although isometric MVC torque is an index of maximal muscle strength, it would not be surprising that neuromuscular fatigue resistance determined in the present study was not related to isometric MVC torque.

Frailty and sarcopenia are linked conditions associated to musculoskeletal aging (Allen et al., 2021; Gandolfini et al., 2019). Frailty has an association with neuromuscular fatigue resistance (Theou et al., 2008), and sarcopenia includes the decline in maximal muscle power (Franchi et al., 2019). Therefore, it is important for older adults to improve both neuromuscular fatigue resistance and maximal power output. Considering the trade-off between high power output ability and fatigue resistance of the KE observed in the current study, an improvement in maximal power output might have a negative impact on neuromuscular fatigue resistance, at least in relative terms. In the future, we should pay attention to this possibility when optimizing training and/or rehabilitation regimens to maintain and improve the quality of life for older adults.

There are several limitations to consider when interpreting the current results. First, some participants had low VA% at Pre as shown in Figure 2c. In particular, the three participants who had very low values of VA% at Pre (74%–83%) showed a significant increase in their values at Post (91%–96%) despite the fact that the participants had practiced isometric MVC of the KE just before the measurements. When considered in conjunction with the fact that the resistance value for the isotonic contractions was calculated from the prefatigue value of MVC torque, the low VA% of these three participants should not be ignored in interpreting the results of the present study.

Therefore, we reanalyzed the results excluding the data of these three participants and confirmed that the reported correlations of neuromuscular fatigue resistance with prefatigue peak power and MVC torque were unchanged. Second, the age range of the participants of the current study (65–88 years) was relatively wide and, consequently, may have influenced the interpretation of the present results. However, the partial correlation between prefatigue peak power and neuromuscular fatigue resistance, controlling for age, was also significant (r = −.524, p = .003). In addition, age was not significantly correlated with either prefatigue peak power (r = −.262, p = .155) or neuromuscular fatigue resistance (r = .127, p = .497). These results suggest a small effect of the age of the participants on the present results. Third, strictly speaking, the measurements at Post were performed during the recovery phase from fatigue except for the isotonic measurements. In particular, the measurements of the

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**Figure 5** — Shear moduli of the RF (a) and VL (b) before and after a fatigue task (Pre and Post; n = 31). Black circles and thick solid lines in the vertical directions indicate means and SDs, respectively. Thin dashed lines indicate individual data. The data were log transformed when analyzing and are presented as raw values. *p value of main effect of time when performing a two-way repeated-measures analysis of variance. RF = rectus femoris; VL = vastus lateralis.

**Figure 6** — Associations between prefatigue peak power (resistance: 20% of prefatigue MVC torque) (a) or prefatigue MVC torque (b) and neuromuscular fatigue resistance for the KEs (n = 31). The data are presented as raw data, and the correlation coefficients were calculated using log-transformed values. MVC = maximal voluntary contraction; KE = knee extensors.
RF and VL shear moduli were completed approximately 3 min after the end of the fatigue task. Given that central fatigue can recover a few seconds after the end of the task in some cases (Mira et al., 2017), the current results of VA% (Figure 2d) and RMS-EMGs of the muscles during isometric contractions (Figure 3) may have been affected by recovery from neuromuscular fatigue. However, it is unlikely that this limitation has any significant impact on the interpretation of the current results because in the present study, central fatigue does not appear to be a main contributor to the fatigue-induced impairments in neuromuscular function even under isotonic conditions (Figure 4). Finally, the participants did not perform a familiarization session on a separate day; thus, the day-to-day repeatability of each variable in the present study is unknown.

Conclusions

In the present study, for older men, fatigue-induced decreases in isotonic peak power, isometric MVC torque, and potentiated twitch torque of the KE were observed. In addition, shear moduli of the RF and VL were increased after the fatigue task. Collectively, these results indicate that impairments in neuromuscular function were likely of a peripheral origin. In addition, those individuals with higher prefatigue power outputs had lower fatigue resistance of the KE for a normalized resistance, highlighting a trade-off between prefatigue maximal power output and neuromuscular fatigue resistance of the KE. This implies that an improvement in maximal power output might have a negative impact on neuromuscular fatigue resistance. Therefore, the findings of the present study are expected to be useful for exploring ways to improve and maintain the quality of life for older adults.

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