Influence of gender on muscle fatigue during dynamic knee contractions

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ABSTRACT. Purpose: The purpose was to compare quadriceps muscle fatigue and change in surface electromyogram (sEMG) spectral power, muscle thickness, and peak torque (normalized by body weight) in men and women during isokinetic knee contractions. Methods: Nineteen healthy volunteers (10 men, 9 women) participated. The volunteers performed 32 consecutive maximal isokinetic knee contractions for peak torque and muscle fatigue index (FI). The sEMG data were analyzed using wavelet analysis for median frequency (MF). Muscle thickness was measured using ultrasonography. Results: Men had a significantly higher FI, peak torque (Nm/kg), muscle thickness than women (p<0.05). A significant linear decreased MF slope in the vastus lateralis was observed (p<0.05) in men than in women. There was no significant difference in MF slope in the vastus medialis between men and women. Conclusion: During muscle fatigue assessment, men had a significantly greater muscle thickness, knee extension peak torque, and a higher decrease of MF slope than women. Our results indicate that specific muscle fatigue observed during repeated muscle knee contractions is significantly influence by gender and affects MF slope, knee extension peak torque, and muscle thickness.

Key words: muscle fatigue, gender difference, quadriceps femoris

Muscle mass, muscle fiber type, and muscle recruitment patterni,ii are strong determinants of quadriceps muscle force-generation. Such muscle force generation is significantly influenced by genderiii. In general, the knee extensor muscle forces are significantly higher in men than in women. However, men have been shown to exhibit a faster rate of knee extensor muscle fatigue than womeniv. This is likely due to a greater muscle mass and higher percentage of fast-twitch muscle fibersv,vi and, the pattern of muscle recruitmentvii. These factors are associated with muscle fatigue. However, few studies have sought to clarify whether there is an influence of gender on muscle mass, the pattern of muscle recruitment and recruitment of fast-twitch muscle fibers during muscle fatigue assessment.

Surface electromyogram (sEMG) is the most widely used noninvasive method to measure muscle activity, muscle recruitment pattern, and fatigue during isometric muscle contraction. It is well known that traditional spectral estimation techniques cannot be assessed in a non-stationary parameter. These techniques assume that the signals are stationary and therefore they cannot cater for the movement component and noise. However, non-stationary parameters have been assessed (e.g., isokinetic or isotonic muscle contractions and cycle-ergometer) by wavelet analysisviii,ix. Change in sEMG spectral power during dynamic knee contractions have been reported to decrease median frequency (MF) in healthy volunteersx,xi. Fast-twitch muscle fibers exhibit higher conduction velocity and increase to a higher MFxii,xi. Interestingly, MF is significantly associated with muscle fiber type compositionsxiii. Little is known about the
relationship between muscle fatigue, muscle mass, and the
pattern of muscle recruitment during dynamic knee contrac-
tions and their association with gender. Moreover, there are
few studies that have attempted to elucidate the key factors
of muscle fatigue between males and females.

Although there are currently insufficient data to sup-
port a causal relationship between muscle fatigue and skele-
total muscle mass or change in MF between males and fe-
males, it is conceivable that this could be measured through
sEMG spectral power and ultrasonography. Assessing the
role of gender in muscle fatigue cannot be estimated with-
out further studies of its measurement in muscle thickness
and sEMG during isokinetic muscle contractions. We meas-
ured the sEMG and ultrasonography findings and isokinetic
muscle strength in healthy volunteers to determine the in-
fuence of gender on the change in MF, muscle thickness,
and muscle fatigue. We hypothesized that gender difference
in muscle fatigue is associated with decrease in the MF
slope of sEMG spectral power and muscle thickness.

In general, gender difference in muscle fatigue has
been considered to be affected by muscle mass, muscle fi-
ter type, and muscle recruitment pattern. However, their
factors has not been examined during muscle fatigue as-
essment at almost the same time. The purpose of this study
was to compare quadriceps muscle fatigue and change in
sEMG spectral power, muscle thickness of the vastus later-
alis (VL), and vastus medialis (VM) and knee extension
peak torque during maximal knee contractions between
men and women.

**Methods**

**Design and setting**

The study used a cross-sectional study design, in
which healthy volunteers from the Hyogo University of
Health Sciences laboratory participated.

**Subjects**

Nineteen healthy volunteers were recruited between
December 2013 and September 2014. The exclusion crite-
ria were experience with resistance training beyond the pre-
vious six months and individuals with a history of cardio-
vacular disease, diabetes, hypertension, or injury. All vol-
unteers provided written informed consent, and the study
was approved by the institutional review board ethics com-
mittee of Hyogo University of Health Sciences. This was
study, protocol no. 13018. We determine sample size using
Gpower 3.1.7, based on a pilot study of five healthy men
and five healthy women in the present study. A power cal-
culated determined that 16 healthy volunteers (eight men
and eight women) would result in a type 1 error rate of 5%
and a type 2 error rate of 20% (80% power). To account for
data error and participant drop-out, we included 20 healthy
volunteers (10 healthy men and 10 healthy women). Base-
line characteristics included 19 healthy [10 healthy men
(age 21.4 ± 0.49 years, height 170.6 ± 5.21 cm, weight
66.11 ± 9.62 kg) and 9 healthy women (age 20.8 ± 1.33
years, height 158.4 ± 3.83 cm, weight 48.57 ± 4.0 kg)] vol-
unteers (data from one volunteer were not included because
she was unable to complete the study protocol). All assess-
ment procedures in this study were administered to all vol-
unteers by one investigator.

**Muscle fatigue assessment**

We measured the knee extensor peak torque and fa-
tigue of the knee extensor muscles using an isokinetic dy-
amometer (Biodex System Version 3, Biodex Medical,
Shirley, NY, USA). Reciprocal concentric isokinetic knee
extension and flexion were assessed at an angular velocity
of 180°/s. Range of motion was a knee angle of 0° to 90°.
Gravity correction was obtained by measuring the torque
exerted on the dynamometer resistance adapter with the
knee in a relaxed state at 10° flexion. The volunteers were
seated on the Biodex dynamometer and were strapped to
the chair in accordance with the Biodex user’s manual.
Lindstrom et al.18 and Pincevero et al.19 reported a linear re-
duction in peak torque over a short period of 30 s.; how-
ever, angular velocity of 60°/s involving 3 s for knee exten-
sion and flexion (knee angle of 0°-90°) and the low repeti-
tion number (10 repetitions) contributed to the high vari-
ance in the muscle fatigue data. Angular velocity of 180°/s
involving 1 s for knee extension and flexion and 30 repeti-
tions have been reported to contribute to a lower variance in
muscle fatigue data compared with angular velocity of 60°/
s. Therefore, in our study, reciprocal concentric isokinetic
knee extension and flexion were assessed at angular veloci-
ty of 180°/s. Owing to the high variance in muscle fatigue
assessment of the first and final repetitions of knee exten-
sion, data from these two repetitions were excluded17). The
volunteers performed 32 consecutive maximal isokinetic
contractions of the knee extensor and flexor muscles. Isoki-
netic knee extensor torque data were recorded as absolute
values (Nm) and subsequently normalized to skeletal mus-
cle mass (Nm/kg). We measured the knee extensor peak
torque to determine the muscle fatigue. Muscle fatigue was
calculated by fatigue index (FI) to yield a present decrease
for each isokinetic knee extensor torque, in a method simi-
lar to that performed by Pincivero et al.18:

\[
FI = 100 - \left( \frac{\text{last five peak torque}}{\text{highest five peak torque}} \right) \times 100
\]

**sEMG measurements**

sEMG was detected from VL and VM of the dominant
thigh throughout the muscle fatigue assessment. Before
sEMG electrodes were placed on the target muscle, the skin
was shaved and cleaned with 95% alcohol to reduce imped-
ance to less than 5 kΩ. Bipolar sEMG electrodes (Blue Sen-
or P; Ambu) were placed on the target muscle according to
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Figure 1. sEMG measurements

Figure 2. sEMG spectrum
A: Vastus lateralis muscle in sEMG spectrum. B: Vastus medialis muscle in sEMG spectrum.

The recommendations from the SENIAM project\(^{19}\) i.e., approximately in line with the pennation angle of the muscle fibers. For each muscle, the inter-electrode distance was 30 mm. A ground electrode was placed on the head of the fibula. The sEMG signals were digitized with 16-bit resolution to a digital converter (Myoresearch XP; Noraxon) at a sampling frequency of 1.5 kHz and stored in a personal computer (Tele MyoG2 EM-601; Noraxon) for subsequent analysis (Fig. 1). The sEMG frequency spectrum was between 12.5 Hz and 200 Hz. For wavelet analysis, Km-Mercury software (Mediarea support business union) was used. Km-mercury software with Gabor filtering was used to calculate the intensity of the wavelet coefficient for the nineteen domains (Fig. 2). The angular information of the Biodex dynamometer was synchronized with the telemetric transmitter during the muscle fatigue assessment. The acceleration and deceleration phases of movement of isokinetic knee extension were excluded (the middle 45 ± 15° of the range of motion were included) from each muscle contractions during the muscle fatigue assessment for wavelet analysis. Owing to the high variance in the sEMG data of the first and final (the 1st and the 32nd) repetitions of maximum knee extension, data from these two repetitions were excluded\(^{13}\). Each knee extension included wavelet analysis for MF.

Muscle thickness

The muscle thickness of VL and VM on the muscle assessment leg was measured using real-time B-mode ultrasonography (Logiqbook XP enhanced; GE Healthcare) with
Measurement of the muscle thickness of the vastus lateralis (VL) and vastus medialis (VM). Muscle thickness was calculated as the length between superficial aponeurose (SA) and deep aponeurose (DA) at three different points (1-1, 2-2, and 3-3) of the ultrasonography image. The mean value of three different points were recorded.

the 50 mm 8-MHz linear probe. To obtain the ultrasonography finding, the volunteers lay in the supine position with their knee extension at 0° and muscle relaxed. Two ultrasonography images were recorded at 2/3 on the line from the anterior superior iliac spine to the lateral side of the patella of VL, and 80% on the line between the anterior superior iliac spine and the joint space in front of the anterior border of the medial ligament of VM. Muscle thickness was calculated as the length between the deep aponeurosis and surface aponeurosis at three different points of the image. Each ultrasonography image was the mean value recorded (Fig. 3). We measured the reliability of the ultrasonography images in this study, resulting in intra-class correlation coefficients of 0.89 and 0.97 for muscle thicknesses of VL and VM, respectively.

Skeletal muscle mass

Skeletal muscle mass (SMM) was assessed by the bio-electrical impedance analysis (Inbody 430; Biospace). The skeletal muscle mass index (SMI) was determined by the following formula for whole body skeletal muscle mass and height:

$$ SMI = \frac{\text{whole body skeletal muscle mass (kg)}}{\text{height}^2 \text{(cm)}} $$

SMM and fat mass were assessed at 4 hours later after a meal.

Statistics

All the analyses were performed using statistical software SPSS Statistics 21.0 (IBM, SPSS Tokyo, Japan). The decline rates of the sEMG spectral for each contraction were calculated using bivariate linear regression to determine MF linear slope. Statistical significance between men and women in FI and peak torque, muscle thickness was determined using a two-tailed unpaired t-test. All values of p < 0.05 were considered significant. Data are shown as mean ± standard deviations (SD).

Results

Gender difference in muscle fatigue, peak torque, and muscle thickness, SMI

The results demonstrated that during muscle fatigue assessment, the men had a significantly higher FI (30.38 ± 6.59%) than the women (21.95 ± 9.19%) (p<0.05). Knee extension peak torque was normalized by body weight, and the women were shown to have a significantly lower peak torque (1.43 ± 0.22 Nm/kg) than the men (1.99 ± 0.19 Nm/kg) (p<0.05) in Table 1. The calculated exponents of the estimated effect size (ES) and 1−β, and 95% confidence intervals (95% CI) using Gpower 3.1.7 for each variable were FI (ES=1.1, 1−β=0.82, 95% CI=0.3 − 16.55) and peak torque (ES=2.7, 1−β=0.99, 95% CI=0.35−0.77). Muscle thickness in VL and VM was significantly greater in the men (VL: 2.05 ± 0.35 cm, VM: 2.12 ± 0.45 cm) than the women (VL: 1.69 ± 0.26 cm, VM: 1.64 ± 0.32 cm) (VL: ES=1.17, 1−β=0.85, 95% CI=0.07−2.0, p<0.05; VM: ES=1.23, 1−β=0.86, 95% CI=0.1−2.04, p<0.05; respectively) (Table 1). SMI was significantly greater in men (SMI=30.98 ± 3.63) than in women (SMI=20.34 ± 0.85, ES=4.03, 1−β=0.99, 95% CI=2.07−5.32, p<0.01).

Gender difference in sEMG spectrum changes

There was a significant linear trend in the decreased MF slope in VL for the men ($y=-0.3777x + 81.391$, adjusted $R^2=0.30$, p<0.01). The men’s VM and women’s VL
Table 1. Male and female characteristics (mean and standard deviations) for FI and peak torque and VL and VM muscle thickness.

<table>
<thead>
<tr>
<th></th>
<th>Men (n=10)</th>
<th>Women (n=9)</th>
<th>ES</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>FI</td>
<td>30.38±6.59*</td>
<td>21.95±9.19</td>
<td>1.1</td>
<td>0.003-1.92</td>
</tr>
<tr>
<td>Peak torque (Nm/kg)</td>
<td>1.99±0.19*</td>
<td>1.43±0.22</td>
<td>2.7</td>
<td>0.35-0.77</td>
</tr>
<tr>
<td>VL muscle thickness (cm)</td>
<td>2.05±0.35*</td>
<td>1.69±0.26</td>
<td>1.17</td>
<td>0.07-2.0</td>
</tr>
<tr>
<td>VM muscle thickness (cm)</td>
<td>2.12±0.45*</td>
<td>1.64±0.32</td>
<td>1.23</td>
<td>0.1-2.04</td>
</tr>
</tbody>
</table>

*Male significantly greater than females (p<0.05). FI, fatigue index. VL, vastus lateralis. VM, vastus medialis. ES, effect size. 95% CI, 95% confidence interval.

Figure 4.

A: Gender difference of median frequency in the vastus lateralis. There was a significant difference in the decrease in median frequency slope between men and women (slope = −0.3777, slope = −0.0281, respectively) (p<0.05). B: There was no significant difference between men and women when assessing the decrease in median frequency slope in the vastus medialis (slope = −0.1941, slope = −0.0708, respectively) (p>0.05). Data are shown as mean of median frequency.

Discussion

Our results support the hypothesis that men have a significantly greater muscle thickness and knee extension peak torque and a higher decrease in the MF slope than women. Moreover, our findings indicated that muscle fatigue was more affected by a decrease in the MF slope and greater knee extension peak torque and skeletal muscle thickness.

Gender difference in muscle fatigue in the quadriceps femoris muscle has been observed in other studies, and men have a significantly greater percentage decrease of muscle fatigue than women. Pincivero et al. examined and reported that the knee extensor peak torque and FI in men and women were 2.11 Nm/kg and 1.53 Nm/kg for peak torque and 39.35% and 33.52% for FI, respectively. Moreover, the gender difference in this present study was similar to those of previous studies that examined muscle fatigue and peak torque. Quadriceps muscle fatigue by the negative slope of knee extensor peak torque, over 30 maximal effort contractions, higher absolute torque values will contribute to a greater per-repetition decrease. Therefore, our results suggest that men have a significantly greater muscle fatigue and peak torque than women.

Our results indicated that male muscle thickness is greater than female muscle thickness for VL and VM. This finding may be explained by the relationship between muscle thickness and muscle strength. In general, maximal muscle strength was reported to correlate with increases in muscle thickness in vivo and in patients. Moreover, cross-sectional muscle is associated with isometric and isokinetic muscle strength.

Recently, sEMG spectral power measurement during muscle fatigue assessment has been reported using wavelet analysis. These studies have shown that MF or mean fre-
quency spectrum decreases during maximal knee extension effort in the quadriceps. The shift of MF power spectra toward lower frequencies decreases with muscle fatigue. This MF power spectra shift is attributed to muscle lactic acidification\(^\text{26,27}\) and potassium accumulation\(^\text{28}\) with reduced intracellular pH and decreased muscle fiber conduction velocity (MFCV)\(^\text{29}\), resulting in an accumulation of metabolites\(^\text{31}\).

As a result, the decrease in MF and MFCV is thought to be associated with a decrease in fast motor unit firing rates\(^\text{32,33}\) and recruitment patterns, which results in the synchronization of motor units. MFCV can affect the MF spectrum, such as motor unit firing and synchronization, and recruitment patterns of the motor unit\(^\text{30}\). However, Masuda et al.\(^\text{31}\) reported that MFCV and MF significantly decrease during isometric contraction, but do not decrease during isotonic contractions. In addition, the difference in muscle contraction type has indicated that blood flow and lactic acid accumulation in muscles determines the relationship between MF and MFCV\(^\text{26,31}\). Because dynamic muscle contractions indicate that oxygen supply is maintained through blood flow compared with that in isometric contractions\(^\text{30}\), the decrease of MF during dynamic muscle contractions is not only explained about gender difference by MFCV and intracellular pH or by accumulation of metabolites. This was because MF slope during muscle fatigue assessment had a similar decrease in men’s VL and women’s VL. However, the study demonstrated that for the men MF slope was shown to have a significantly greater decrease in slope than women. However, the sEMG signal recorded during muscle contractions was significantly associated with muscle fiber type composition and MF. In addition, Staron et al.\(^\text{32}\) used muscle biopsies taken from VL of untrained healthy volunteers and reported that muscle fast fiber types are predominant in men, whereas slow fiber types tended to be predominant in women. Interestingly, muscle fiber composition of VL is different from that of VM. Other data have shown that VL and VM of type 2 muscle fiber were 67.3% and 56.3%, respectively\(^\text{33}\). Moreover, the cross sectional area of type 2 fiber was larger in men compared with women\(^\text{34}\). However, the study design in those studies was specific for the investigation of muscle biopsies for the assessment of gender difference on muscle fiber type. Simonneau JA, et al.\(^\text{35}\) and Staron RS, et al.\(^\text{31}\) reported that women VL muscle has been demonstrated that exhibit a greater proportion and smaller type 1 muscle fibers than men, whereas type 1 fibers tended to be the largest in women. Green et al.\(^\text{36}\) reported that women have a significantly lower overall capacity for aerobic oxidation and anaerobic glycolysis compared with men. Furthermore, glycolytic potential is lower in women. In the present study, the women’s MF slope may be explained by the lower glycolytic potential (lower accumulation of metabolites compared with men) and maintenance of oxygen supply by dynamic muscle contractions. Consequently, muscle recruitment pattern and muscle mass significantly influenced gender difference.

In conclusion, this study provides a gender difference during muscle fatigue assessment where men had a significantly greater muscle thickness and knee extension peak. The shift of MF power spectra toward lower frequencies decreases with muscle fatigue. This MF power spectra shift is attributed to muscle lactic acidification and potassium accumulation with reduced intracellular pH and decreased muscle fiber conduction velocity (MFCV), resulting in an accumulation of metabolites. As a result, the decrease in MF and MFCV is thought to be associated with a decrease in fast motor unit firing rates and recruitment patterns, which results in the synchronization of motor units. MFCV can affect the MF spectrum, such as motor unit firing and synchronization, and recruitment patterns of the motor unit. MFCV and MF significantly decrease during isometric contraction, but do not decrease during isotonic contractions. In addition, the difference in muscle contraction type has indicated that blood flow and lactic acid accumulation in muscles determine the relationship between MF and MFCV. Because dynamic muscle contractions indicate that oxygen supply is maintained through blood flow compared with that in isometric contractions, the decrease of MF during dynamic muscle contractions is not only explained by gender difference by MFCV and intracellular pH or by accumulation of metabolites. This was because MF slope during muscle fatigue assessment had a similar decrease in men’s VL and women’s VL. However, the study demonstrated that for the men MF slope was shown to have a significantly greater decrease in slope than women. However, the sEMG signal recorded during muscle contractions was significantly associated with muscle fiber type composition and MF. In addition, Staron et al. used muscle biopsies taken from VL of untrained healthy volunteers and reported that muscle fast fiber types are predominant in men, whereas slow fiber types tended to be predominant in women. Interestingly, muscle fiber composition of VL is different from that of VM. Other data have shown that VL and VM of type 2 muscle fiber were 67.3% and 56.3%, respectively. Moreover, the cross sectional area of type 2 fiber was larger in men compared with women. However, the study design in those studies was specific for the investigation of muscle biopsies for the assessment of gender difference on muscle fiber type. Simonneau JA, et al. and Staron RS, et al. reported that women VL muscle has been demonstrated that exhibit a greater proportion and smaller type 1 muscle fibers than men, whereas type 1 fibers tended to be the largest in women. Green et al. reported that women have a significantly lower overall capacity for aerobic oxidation and anaerobic glycolysis compared with men. Furthermore, glycolytic potential is lower in women. In the present study, the women’s MF slope may be explained by the lower glycolytic potential (lower accumulation of metabolites compared with men) and maintenance of oxygen supply by dynamic muscle contractions. Consequently, muscle recruitment pattern and muscle mass significantly influenced gender difference.

In conclusion, this study provides a gender difference during muscle fatigue assessment where men had a significantly greater muscle thickness and knee extension peak.
torque and a greater decrease of the MF slope in VL than women. In addition, our results indicate that specific muscle fatigue observed during repeated muscle knee contractions associated with gender difference is influenced by the decrease of the MF slope in VL and knee extension peak torque and muscle thickness.

References