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Original research

Divergent muscle fatigue during unilateral isometric contractions of dominant and non-dominant quadriceps

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A B S T R A C T

Objectives: We examined mechanical and electromyographic responses of unilateral dominant and non-dominant *m. quadriceps femoris* during fatiguing submaximal isometric contractions and early recovery.
Design: Within subjects randomized.
Methods: Healthy males ($n = 18$, age: 20 ± 2 yr, height: 181 ± 7 cm, and body mass: 79.4 ± 10.5 kg) attended two sessions. Leg dominance was based on the preferred kicking leg. Maximal voluntary isometric force, endurance time and force fluctuations during a 20%MVIF until exhaustion were measured simultaneously with surface electromyography (EMG) of *m.vastus lateralis* and *m.vastus medialis* at a knee angle of 90° as well as the MVIF 20 s after exhaustion (early recovery).
Results: The maximal voluntary isometric force of dominant *m. quadriceps femoris* was 4.6% higher (D: 749 ± 178 N, ND: 716 ± 184 N, and $P = 0.01$). The *m. quadriceps femoris* of both legs had similar endurance times during the 20%MVIF (D: 367 ± 157 s, ND: 381 ± 153 s, and $P = 0.40$). Force fluctuations during the 20%MVIF increased over time (two-way ANOVA, $P < 0.05$) with no differences between legs at comparable time points. Changes in median frequency and root mean square of *m.vastus lateralis* and *m.vastus medialis* during the 20%MVIF were similar for both legs. However, after the 20%MVIF, early recovery, quantified by the fatigue index, showed larger force loss for dominant *m. quadriceps femoris* (D: 39.9 ± 15.7%, ND: 34.8 ± 16.0%, and $P < 0.05$).
Conclusions: Muscle fatigue that develops during submaximal sustained isometric contractions may not be accurately quantified by force loss soon after exhaustion. The present study has implications for unilateral studies to examine mechanisms of muscle fatigue.

1. Introduction

Muscle fatigue has been defined as an exercise-induced reduction in the ability to produce maximal force.[1] This definition is pragmatic, widely accepted, and allows unequivocal quantification of exercise-induced muscle fatigue. The progression and mechanisms of exercise-induced muscle fatigue are related to the intensity and duration of the exercise and can result from different origins and mechanisms. Furthermore, the origin of muscle fatigue is related to the type of muscle contraction.[2,3] During voluntary sustained isometric contractions at low intensities, muscle fatigue is known to develop from a progressive contribution of both neural and muscular mechanisms (i.e. central and peripheral fatigue).[4,5]

Previous studies on muscle fatigue by voluntary sustained isometric contractions illustrated that a difference in time to failure of a task due to age[6] or sex[7] were interpreted as a difference in the fatigue resistance of skeletal muscles. Although a different time to task failure has been taken to establish differences in muscle fatigue, an additional measurement of the reduced maximal force producing ability soon after task failure is commonly performed and essential to allow quantification of the exercise-induced muscle fatigue[6] according to the definition by Søgaard et al.[1] Therefore, one may expect that a similarity in time to task failure for sustained isometric contractions by similar fatigue processes in skeletal muscles of an individual would be associated with similar post-exercise measurement of muscle fatigue by production of maximal voluntary force. However, it is not known whether this would occur. Also, the development of fatigue during a sustained isometric contraction is associated with an increase in the fluctuations of the force around a mean target force[8–10] with simultaneous increases in EMG activity.[11] Similarity in time to task failure in an individual would be expected to be associated with similar changes in fluctuations of force and changes in surface EMG parameters during the fatiguing task. Experiments to examine such responses to muscle fatigue have used primarily the methodological approach of testing a single limb.[12,13] Potential differences in fatigue responses between limbs have been ignored.

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Studies on muscle fatigue that implemented a unilateral or bilateral approach have shown greater time to task failure with one leg.[14] Such studies have clearly illustrated that muscle fatigue and motor unit activation are task-dependent.[15] However, it is not known whether a similarity in the requirements of a fatiguing isometric task for both legs and tested independently from each other would provide similar responses. Although attention has been given to skeletal muscles of dominant and non-dominant legs with respect to unilateral postural control,[16] torque of quadriceps muscles,[17] the cross-over effect of muscle fatigue,[18] and performance of isokinetic contractions,[19] whether there is uniformity between legs for the fatigue resistance to submaximal isometric contractions is not known. There is the possibility that the variability in skeletal muscles between non-dominant and dominant legs with respect to muscle mass, fiber type, cross-sectional area, localized blood flow and accumulation of metabolites may influence the fatigue resistance. Dominant and non-dominant skeletal muscles may show discrepancies in their responses to a fatiguing protocol.[20]

Therefore, the aim of the present study was to examine muscle fatigue and electromyographic responses of the *m. quadriceps femoris* of the dominant and non-dominant legs during submaximal sustained voluntary isometric contractions and early recovery. The findings of this study may have implications for unilateral studies on muscle fatigue.

2. Methods

Healthy physically active male university students ($n = 18$, age: 20 ± 2 yr, height: 181 ± 7 cm, and body mass: 79.4 ± 10.5 kg) volunteered to participate in the present study. Participants had no history of joint problems for the knee and ankle. All experimental procedures were approved by the Ethics committee of the University of Chichester and performed according to the Declaration of Helsinki. Participants were informed about the procedures and purposes of the study and provided written informed consent prior to entering the study. All participants were familiarized for performance of force measurements with isometric contractions of the *m. quadriceps femoris*. The main goal of the experiments was to determine the mechanical and electromyographic responses of the *m. quadriceps femoris* of the dominant and non-dominant legs during maximal voluntary isometric contractions (i.e. maximal voluntary isometric force, MVIF), time to task failure for a submaximal voluntary isometric contraction (i.e. 20%MVIF) and early recovery from a 20%MVIF. Each testing session consisted of (1) three submaximal warm-up contractions, (2) three maximal voluntary isometric contractions, (3) a 20%MVIF test to exhaustion and (4) a MVIF 20 s after exhaustion. All mechanical recordings and surface electromyography were measured in two separate randomized sessions at the same time of the day with at least 48 h between sessions.

Force recordings of the *m. quadriceps femoris* occurred with the participants seated in a custom-built chair. The upper body was kept firmly restrained against the back of the chair using strap belts over chest and lower thigh. Both hip and knee joint angles were kept at 90° (full extension is 0°). Participants had their arms across the chest during all force testing. The ankle of the participant was connected with a chain to a calibrated stainless steel force transducer (model 616, Tedea-Huntleigh, Cardiff, UK) with a maximum of 2500 N. Real-time force was recorded by the force transducer and PowerLab data acquisition system (ADinstruments Ltd., Oxford, UK) and displayed using Chart for Windows (v. 3.4.1) on a computer screen positioned about 1.5 m in front of the subject. The force signal was sampled and stored with a frequency of 1000 Hz. Subjects performed three warm-up contractions (duration 4–6 s) with a rest time of 1 min at an estimated intensity of about 30% of the force during maximal voluntary isometric contractions (MVIF). The 30% intensity was based on familiarization data. Subsequently, participants were instructed to perform three "all-out" maximal voluntary isometric contractions (MVIF) for about 2–5 s with a recovery time of 2 min between trials. Participants were encouraged to exceed the maximum force value visible on the computer screen. Consistent strong verbal encouragement was provided during MVIF.[21] Following the MVIF, the monitor screen information for the Chart for Windows program was adjusted so that top and bottom of the screen represented 0%MVIF and 40%MVIF, respectively. The target force for 20%MVIF was shown as a narrow horizontal bar in the middle of the screen. For the 20%MVIF test, participants were instructed to gradually increase the contraction force to a level matching the horizontal bar. Start of the endurance time was taken when the force signal was between 17.5% and 22.5%MVIF for at least 2 s. The failure point was the time at which force fell below 17.5%MVIF for longer than 3 s when testing was stopped by the experimenter. Time analysis of start and failure point occurred post-exercise. During the test, the experimenter knew where in the screen the force was 17.5%MVIF for the decision to stop the test.

Participants received strong verbal encouragement during mechanical testing. Our protocol allowed subjects to produce force values with the *m. quadriceps femoris* close to 20%MVIF (i.e. non-dominant: 20.1 ± 1.3% and dominant: 20.0 ± 1.3%). Twenty seconds on completion of the isometric fatigue task, subject performed one final "all-out" MVIF. This time was chosen to allow the experimenter to return the computer screen settings of the Chart software back to the settings before the 20%MVIF.

Bipolar surface EMG electrodes (Delsys, Boston, MA, USA), consisting of two parallel silver (99.9%) bars, each 10 mm in length and 1.0 mm wide, with a interelectrode distance (center-to-center) of 10 mm, were placed over the *m. vastus medialis* (VM) and *m. vastus lateralis* (VL). The common-mode rejection ratio of the EMG electrodes was <92 dB. The reference electrode was placed over the patella. Before electrode placement, the skin was shaved, lightly abraded to reduce impedance between the electrode and cleansed with alcohol swabs. Electrodes were fastened to the skin with tape and location was identified to enable electrode placement at the same location in various sessions. Raw EMG signals were amplified ($\times 1000$) per channel, sampled at a rate of 1024 Hz and stored on computer.

For each MVIF, the maximal isometric force was quantified as the highest mean value over a 0.5 s period that included the peak isometric force. The maximal isometric force measured during any of the three trials was then taken as a measure of MVIF (i.e. $MVIF_{pre}$). Force fluctuations during the sustained isometric contraction were quantified as the coefficient of variation for force (i.e. $CV = SD/mean \times 100\%$). Fatigue induced by the sustained isometric contraction was quantified by the ratio (percent) of the force value 20 s after completion of the isometric fatigue task (i.e. $MVIF_{post\ 20\,s}$) to the maximal force value of the MVIF before the isometric fatigue task (i.e. $MVIF_{pre}$) (referred to as early recovery):

$$\text{Fatigue index}\quad(\%) = 100 - \frac{MVIF_{post\ 20}}{MVIF_{pre}} \times 100$$

EMGworks software (Delsys, Boston, MA, USA) was used for band-pass filtering (20–500 Hz) of the raw EMG signals and calculation of the EMG parameters root mean square (RMS) (window length: 0.05 s and window overlap: 0.025 s) and median frequency (MDF) during 20%MVIF (window length: 1.0 s and window overlap: 0.5 s) for each muscle. The RMS (quantifying the EMG amplitude) and MDF values were taken as an index of muscle activity and muscle fatigue, respectively. EMG parameters for the 20%MVIF (i.e. MDF and RMS) were calculated for successive sampling intervals for the start (0–10%), middle (45–55%) and end (90–100%) of the time to