High Risk of Muscle Strain in the Rectus Femoris Muscle: 
Anatomical and Physiological Analysis

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Objective: Clinical studies reported that the muscle strain of the quadriceps femoris muscles (QF) is most frequent in the rectus femoris (RF) with specific postures. The mechanism underlying the specificity of muscle strain has not been fully understood. We postulated that the physiological and anatomical properties of the muscles constituted a main risk factor of muscle strain.

Materials and Methods: Knee extension torque and surface electromyographic (EMG) signals were measured in 18 healthy adults. Anatomical specimens of QF were obtained from 9 cadavers.

Results: Isometric knee extensor torque was smallest at knee angle of 10° and gradually increased at larger knee angles of 30°, 60°, and 90°. EMG activities during isometric contraction of the three QF muscles were at a similar level during knee flexion at angles from 10° to 30°, 60°, and 90°, except for a slight non-significant increase at 90° in the vastus lateralis (VL) and the vastus medialis (VM). The four muscles of QF had pennate structure, and their muscle fiber length per total muscle length (FL/TML) was not significantly different. In RF, the muscle fibers were more extended with flexed knee joint and extended hip joint than in the other muscles.

Conclusions: The specific high incidence of muscle strain in RF was explained on the basis of physiology and anatomy. In addition, the rationale presented in the present study would be helpful to decrease the incidence of muscle strain by specific exercise to increase the force and extensibility of RF.

Key words: quadriceps femoris muscles (QF), rectus femoris (RF), muscle strain, electromyographic (EMG) acticity

Introduction

The quadriceps femoris (QF), comprising the rectus femoris (RF), vastus intermedius (VI), vastus lateralis (VL), and vastus medialis (VM), is known to have a high incidence of muscle strain, as these muscles repeatedly exert a powerful muscular force during exercise1-3. The muscle strain represents injury in the muscular tissue due to excessive and violent extension of muscle fibers1. Many clinical-based reports indicate that strain of QF is the most frequent occurrence next to the hamstrings3 5. The most commonly strained muscles were RF in the preseason of football players, as RF would be heavily involved in both running and shooting3. It is reported that injuries commonly occur during hip extension and knee flexion5 6, and that a particularly high incidence of strain has been observed in RF3 5. Although one may guess that RF may be extended extremely during hip extension and knee flexion, the degree of extension as well as the muscle activity of RF and the other muscles of QF during the exercise have never been quantitatively analyzed yet.

In the present study, QF muscles were analyzed both physiologically and anatomically on a hypothesis that the muscle strain is caused by excessive extension of muscle fibers by excessive force. For
the physiological study, knee extensor torque and surface electromyographic (EMG) signals were measured during isometric contraction of QF. For the anatomical study, the orientation and length of muscle fibers were recorded, and the morphological changes of individual muscles during hip joint flexion and knee flexion were quantitatively measured.

Material and methods

1. Participants

Knee extension torque in isometric contraction was measured in 18 healthy males and females. Average age of the subjects was 19.5 ± 2.0 years for males and 18.6 ± 1.0 years for females. Average height was 173.8 ± 5.5 cm for males and 158.3 ± 6.6 cm for females, and average body mass was 69.9 ± 11.9 kg for males and 51.9 ± 6.3 kg for females. All subjects were informed of the purpose and risks of the study and provided written informed consent. Participants provided written informed consent before measurement of knee extension torque and surface EMG.

Specimens of legs for morphological analysis of QF were obtained from 9 cadavers (5 males and 4 females) which were used in the anatomy dissection course of School of Medicine during the 2011-2012 academic year. Approval of the study was obtained from the Ethical Committee of Juntendo University (No. 2012156).

2. Experimental Design

1) Measurement of knee extension torque and surface EMG

Knee extension torque in isometric contraction was measured using a muscle strength dynamometer (BIODEX, Biodex System 3, Shirley, NY). Measurements were taken twice in the supine position and neutral hip position under four conditions, with knee flexion at 10°, 30°, 60°, and 90° for 5 s during maximum voluntary contraction. To prevent hip flexion while taking measurements, the hips were tightly secured with a belt at 0° hip flexion. Intervals were left between each measurement to enable sufficient rest to be taken.

Along with knee extension torque, the amount of muscle activity for RF, VL and VM was simultaneously measured using surface electromyography (NORAXON Telemyo 2400, Scottsdale, AZ) at a sampling rate of 1,500 Hz. Placement of bipolar surface electrodes on the muscles was determined according to Delagi et al.7. To reduce skin resistance, the skin was shaved and rubbed with alcohol before attaching active electrodes.

Active electrodes were placed midpoint between the superior border of the patella and the superior anterior iliac spine for RF, at points 5-finger breadths proximal and 2-finger breadths lateral to the superior lateral border of the patella for VL, and at a point 4-finger breadths proximal and 2-finger breadths medial to the superior medial border of the patella for VM. Verification of electrodes was conducted in advance by B-mode ultrasonic tomography.

EMG recordings were converted from analog to digital and stored as raw data on a personal computer. Digitized data were then rectified and analyzed using Myoresearch XP Master Edition (NORAXON, Scottsdale, AZ) software. Root mean square electromyography (RMS-EMG) value was integrated for 2 s after 1 s from the start of isometric contraction because the EMG wave pattern was stabilized in this time interval.

2) Morphology of QF

We measured total muscle length (TML) in the four QF muscles in the specimens obtained at full knee extension and hip extension. We measured TML as the distance between the origin and insertion of individual muscles including tendon, and measured changes of TML in the four muscles by adjusting the angle of the knee joint. Finally, we adjusted the angle of the hip joint and only measured changes of TML in RF. Morphological measurements of the four QF muscles were conducted in accordance with the procedures used in a previous study on the hamstrings8. TML of each muscle was measured with knee flexion at 30°, 60°, and 90°. Furthermore the length of RF was measured with hip flexion at 30°, 60°, and 90° and knee flexion at 0°, 30°, 60°, and 90°.

After separation of the individual muscles, muscle fiber length (FL) and pennation angle (θ) were measured at the proximal, middle and distal portions in the three vastus muscles, and at the proximal, left middle, right middle and distal portions in RF, and the measured values were averaged in the individual muscles. The pennation
angles were measured at the distal myotendinous junction as the deviation of the angles between the muscle fibers and tendon fibers. On the basis of these data and muscle mass (M), the physiological cross-sectional area (PCSA) was calculated using the following formula:

\[ \text{PCSA (cm}^2\) = M (g) \times \cos \theta / \rho (g/cm}^3\) \times \text{FL (cm)} \]

From the data of TML and FL, we calculated the relative value of FL compared with TML for each muscle of QF (FL/TML). The changes in muscle length were calculated from the measurements in four conditions, with knee flexion at 0°, 30°, 60°, and 90° (\(\Delta \text{TML}_{30°-0°} \), \(\Delta \text{TML}_{60°-0°} \), \(\Delta \text{TML}_{90°-0°} \)) for VL, VM and VI, and from those in 16 conditions, with hip joint flexion at 0°, 30°, 60°, and 90° and knee joint flexion at 0°, 30°, 60°, and 90° for RF. The data were three-dimensionally graphed by Microsoft Excel. The relative values of TML change compared with FL were calculated (\(\Delta \text{TML}_{30°-0°} / \text{FL} \), \(\Delta \text{TML}_{60°-0°} / \text{FL} \), \(\Delta \text{TML}_{90°-0°} / \text{FL} \)).

3. Statistical analyses

Statistical analyses are conducted using the SAS software program (SAS Institute Inc.). All values are presented as mean ± standard deviation. Integrated RMS-EMG values was analyzed by one-way analysis of variance (ANOVA) and multiple comparison Dunnett’s test. With regard to torque (Nm), the mean value 2 s after 1 s from the start of exhibiting a stable force was divided by body mass (kg) and multiplied by 100.

Morphological measurements values of the four QF muscles were examined by one-way analysis of variance (ANOVA) and by multiple comparison tests (Dunnett’s, Bonferroni). A P value of 0.05 was considered statistically significant.

Results

1. Measurement of knee extension torque and surface EMG

To clarify the functional properties of QF, we measured knee extension torque as well as surface EMG activity of three of the muscles (RF, VL, VM). Based on the data obtained, EMG activities of the 3 muscles of QF were calculated.

Knee extension torque during isometric contraction of QF (Nm/kg * 100) was 72.0 at 10° of knee angle, 117.1 at 30°, 224.5 at 60° and 278.7 at 90°. QF generated greater knee extension torque as the degree of knee flexion increased. (Figure–1)

EMG activities during isometric contraction of the three QF muscles were at a similar level during knee flexion at angles from 10° to 30°, 60°, and 90°, except for a slight non-significant increase at 90° in VL and VM. Between RF, VL and VM, no significant differences were observed at any angle of knee flexion.

2. Morphology of QF

QF consists of one rectus and three vastus muscles. RF contained a slender proximal tendon beginning from the os coxae on the superficial side.
and a broad distal tendon on the deep side of the muscle, and possessed pennate construction with parallel arrangement of muscle fibers between the tendons. VL and VM contained a broad proximal tendon on the superficial side and a broad distal tendon on the deep side of the muscle, respectively. VI muscle arose directly from the femoral bone and terminated via a distal tendon on the superficial side of the muscle (Figure-3). The three vastus muscles possess pennate construction with parallel arrangement of muscle fibers between the two sides of the muscle.

TML, FL, and FL/TML were strikingly similar among the four muscles and showed no significant differences (Table-1). ΔTML/FL by knee flexion (30°, 60°, and 90°) from the extended position (0°) were also strikingly similar among the four QF muscles (Table-2). ΔTML/FL by knee flexion and hip extension together was about twice that by either knee flexion alone or hip extension alone (Figure-4). On the other hand, PCSA was significantly different among the four muscles, with the lowest value in RF (8.5 ± 3.1), and the largest value in VL (34.4 ± 14.0) (Table-3).

Discussion

Functional studies of knee extension torque and EMG activity of QF have not been performed to clarify the mechanism of muscle strain. In addition, the anatomical architecture of the four QF muscles in terms of the disposition of tendons and arrangement of muscle fibers has not been well investigated[6] [14]-[18], although it is intimately correlated with functional properties of these muscles. Textbooks on anatomy seldom refer to the architecture of RF, except for superficial bipennate appearance of RF[17] [18].

In the present study, isometric knee extensor torque was smallest at knee angle of 10° and gradually increased at larger knee angles of 30°, 60°, and 90°. Similar gradual increase of knee extensor torque was reported in previous studies with greatest torque either at 90° or about 70° [19] [20]. Considering the relatively constant level of moment.
arm length of patellar tendon for knee extension at different angles\textsuperscript{21,22}, the tension of QF was expected to be the greatest by deep knee flexion, hence the risk of muscle strain for QF was expected to be the greatest by deep knee flexion.

EMG activity of the three QF muscles was measured during maximal isometric contraction to estimate the relative contribution of the individual muscles to the total tension of QF. During deep knee flexion at 90°, EMG activity was not significantly different among the three muscles, which was 623.0 μV × s in RF, 757.3 μV × s in VL, and 681.6 μV × s in VM.

We measured maximum isometric knee extensor
torque at different knee angles, and determined that knee extensor torque during knee flexion increased significantly at larger knee angles compared with that at 10°. Previous studies have also reported similar increase of extensor torque by knee flexion\textsuperscript{19, 20}. On the other hand, these results are apparently inconsistent with the similar levels of EMG activity at different knee angles found in the present study and also reported in previous studies\textsuperscript{20}. This discrepancy may be explained by the complexity of the determinants of knee extensor torque. Torque of joint movement is defined as the production of muscle force by the moment arm\textsuperscript{23}, and in the case of knee joint the moment arm is not constant, but variable during knee flexion, since the attachment site of the femoral condyle to the tibial condyle moves during knee flexion.

We clarified the disposition of origin and insertion tendons as well as arrangement of muscle fibers within QF. In addition we measured TML and FL morphometrically, as in a previous study on the biceps femoris\textsuperscript{8}. In that study, the morphological parameters were correlated with the functional data on the muscles to evaluate the high risk of muscle strain in the long head of biceps femoris with hemi-pennate architecture.

As shown by Kumazaki et al.\textsuperscript{8}, relative muscle fiber length (FL/TML) and relative increase of TML ($\Delta$TML/FL) by joint movement are good estimators of the risk of muscle strain. The present study revealed that the four QF muscles had similar values of both FL/TML and $\Delta$TML/FL, indicating no higher risk of muscle strain in RF. However, TML of RF increases not only by knee flexion but also by hip extension, because RF spans both the knee and hip joints. When the movement of the 2 joints are coupled, $\Delta$TML/FL of RF became about twice that by either movement alone, indicating higher risk of muscle strain in RF than in the other muscles of QF, especially at limb position with extended hip joint and flexed knee joint, as shown in clinical data\textsuperscript{5, 6}.

From the morphological analysis of QF, we clarified that the muscle fibers of RF were being stretched to a greater extent than those of the other three muscles, indicating that their sarcomere would be extended excessively resulting in higher risk of muscle strain. Ward et al.\textsuperscript{12} measured systematically the macroscopic architecture and in addition the microscopic sarcomere length of lower extremity muscles, and revealed that hip flexors and knee flexors had larger sarcomere length indicating the elongation of sarcomere in these muscles in fixed cadavers\textsuperscript{20, 21}. However, contrary to their supposition that the standard sarcomere length was homogeneous among muscles, their data indicate considerable variation of sarcomere length even within the same muscle group. Extensive variation of sarcomere length among muscles was already evident from the data provided by Wickiewicz et al.\textsuperscript{13}. We believe that our macroscopic analysis would more informative than the microscopic analysis of sarcomere to understand the mechanism of muscle strain.

The strain of QF frequently occurs in sports that require repetitive kicking and sprinting actions when the hip joint is extended\textsuperscript{1, 26}. RF is the most commonly injured muscle among the four QF muscles\textsuperscript{5, 6}. The kicking action in football requires frequently maximal hip extension and knee flexion resulting in combination of strong contraction and extreme stretching of RF\textsuperscript{27}. In the present study, we demonstrated that the risk of muscle strain was higher with flexed knee joint and extended hip joint in RF which moves both joints. The present study employing physiological and anatomical approaches contributes to our understanding of the mechanism underlying the specificity of muscle strain in RF. The possibility that the pelvic balance may affect the risk of muscle strain of RF is a subject of future studies.

The present study would provide a beneficial advice to prevent the muscle strain of RF. The exercises to increase both the force and extensibility of RF would be highly beneficial, as usually performed for the hamstrings as Nordic hamstring exercise. However, either simple flexion of the hip joint or simple extension of the knee joint is performed by RF and the other muscles including iliopsoas and three vastus muscles, and does not extend RF sufficiently, since RF acts on both the joints. To increase both the force and extensibility of RF, muscle contraction during maximal extension of the knee joint is performed by RF and the other muscles including iliopsoas and three vastus muscles, and does not extend RF sufficiently, since RF acts on both the joints. To increase both the force and extensibility of RF, muscle contraction during maximal extension of the knee joint is desired, as recently proposed to prevent muscle injury of RF as reverse Nordic hamstring\textsuperscript{20}. In the exercise, the player kneeling on the soft ground with his ankle fixed followed by slowly backward lowering himself to the ground eccentrically contracting quadriceps muscle.
followed by explosive return to start position. It should be noted that the present study is pure theoretical in nature hypothesizing that the muscle strain is caused by excessive extension of muscle fibers by excessive force, and explains well high incidence of muscle injury of RF in specific postures among four muscles of QF. Because of the theoretical nature, the present study does not predict specific localization of injury within the muscle or severity of injury in the individual cases.

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Conflict of interests

The authors declare no conflict of interest associated with this manuscript.

References