Available online at www.sciencedirect.com
ScienceDirect
Journal of Sport and Health Science xx (2016) 1–5
www.jshs.org.cn

Original Article

Stiffness of individual quadriceps muscle assessed using ultrasound shear wave elastography during passive stretching

Jingfei Xu [a,b,c], François Hug [d,e], Siu Ngor Fu [b,*]

[a] Department of Rehabilitation Medicine, West China Hospital, Sichuan University, Chengdu 610041, China
[b] Department of Rehabilitation Sciences, The Hong Kong Polytechnic University, Hong Kong, China
[c] Institute for Disaster Management and Reconstruction, Sichuan University, Chengdu 610207, China
[d] The University of Queensland, NHMRC Centre of Clinical Research Excellence in Spinal Pain, Injury and Health, School of Health and Rehabilitation Sciences, Brisbane 4072, Australia
[e] Laboratory "Movement, Interactions, Performance" (EA 4334), University of Nantes, Nantes 44000, France

Received 11 December 2015; revised 1 February 2016; accepted 19 February 2016
Available online

Abstract

Background: Until recently it has not been possible to isolate the mechanical behavior of individual muscles during passive stretching. Muscle shear modulus (an index of muscle stiffness) measured using ultrasound shear wave elastography can be used to estimate changes in stiffness of an individual muscle. The aims of the present study were (1) to determine the shear modulus–knee angle relationship and the slack angle of the vastus medialis oblique (VMO), rectus femoris (RF), and vastus lateralis (VL) muscles; (2) to determine whether this differs between the muscles.
Methods: Nine male rowers took part in the study. The shear modulus of VMO, RF, and VL muscles was measured while the quadriceps was passively stretched at 3°/s. The relationship between the muscle shear modulus and knee angle was plotted as shear modulus–angle curve through which the slack angle of each muscle was determined.
Results: The shear modulus of RF was higher than that of VMO and VL when the muscles were stretched over 54° (all $p < 0.01$). No significant difference was found between the VMO and VL (all $p > 0.055$). The slack angle was similar among the muscles: 41.3° ± 10.6°, 44.3° ± 9.1°, and 44.3° ± 5.6° of knee flexion for VMO, RF, and VL, respectively ($p = 0.626$).
Conclusion: This is the first study to experimentally determine the muscle mechanical behavior of individual heads of the quadriceps during passive stretching. Different pattern of passive tension was observed between mono- and bi-articular muscles. Further research is needed to determine whether changes in muscle stiffness are muscle-specific in pathological conditions or after interventions such as stretching protocols.

Keywords: Muscle tension; Shear modulus; Slack angle; Stretch; Ultrasonography; Vastus lateralis; Vastus medialis; Optimal length

1. Introduction

Flexibility is classically assessed at the joint level by measuring the maximum range of motion or the joint torque during passive motion.[1] However, these measures are influenced by the contribution of many structures crossing the joint including muscles, nerves, and skin. Hence, the behavior of individual muscles is not directly represented. This is problematic as there is recent evidence that stretching-induced change in muscle stiffness may differ between individual muscles that belong to the same muscle group such as hamstring muscles.[2] Therefore, it is important to assess each individual muscle for a deeper understanding of muscle flexibility and to improve musculoskeletal models.

Ultrasound shear wave elastography is a technique to quantify the stiffness of a localized area of soft tissue. An elastography technique called supersonic shear imaging (SSI) provides an accurate quantification of muscle shear modulus[3] that can be considered as a measure of muscle stiffness.[4] Because there exists a strong linear relationship between muscle stiffness and passive tension when passively stretching the muscle,[5] changes in muscle stiffness measured using SSI can be used to estimate tension changes of muscle responding to passive stretch.[6] In addition, the SSI method provides an

Peer review under responsibility of Shanghai University of Sport.
* Corresponding author.
E-mail address: amy.fu@polyu.edu.hk (S.N. Fu)

http://dx.doi.org/10.1016/j.jshs.2016.07.001

opportunity to estimate the slack angle of individual muscles which is defined as the joint angle beyond which muscles begin to develop passive tension.[7]

Taking advantage of SSI, changes in muscle stiffness have been estimated during passive stretching in humans, mainly on the medial gastrocnemius,[7–9] soleus,[8] tibialis anterior,[10] and biceps brachii muscle.[11] All these studies confirmed the classic exponential relationship between passive muscle tension and muscle length. Interestingly, different stiffness values were reported between muscles belonging to the same muscle group such as hamstring muscles.[2] Further, Hirata et al.[8] demonstrated that the individual heads of the triceps surae exhibit a different slack angle during passive dorsiflexion with larger plantar flexed angle for the medial gastrocnemius than the lateral gastrocnemius and the soleus. In contrast, both heads of the biceps brachii muscle have the same slack angle at about 95° elbow flexion.[11]

It is important to assess the passive behavior of the quadriceps muscle heads from both a clinical and basic sciences perspective. First, the quadriceps muscle is a large muscle group that is exposed to large strain while individuals perform pushing/pulling movements and running or jumping actions.[12] As a consequence, along with the hamstrings and triceps surae, quadriceps is 1 of the 3 muscle groups that are the most susceptible to be injured in athletes.[13] The strain injuries commonly occur in the rectus femoris (RF) muscle,[14] suggesting that the stiffness of the RF muscle is higher than that of the other mono-articular heads. Second, although biomechanical models often consider that the slack angle of muscle is similar to the optimal angle at which the maximal force can be generated,[10,15] there exists no experimental evidence of this assumption. SSI provides a unique opportunity to test this assumption.

We designed this study (1) to determine the passive stiffness–angle relationship and the slack angle of the vastus medialis oblique (VMO), RF, and vastus lateralis (VL) muscles; (2) to determine whether this differs between muscles. Muscle shear modulus (an index of stiffness) was measured using SSI during passive knee flexions. The vastus intermedius (VI) muscle was not recorded because its location underneath VM, VL, and RF made challenging to get reliable measurements.

2. Materials and methods

2.1. Participants

Nine male rowers without history of leg injury (age: 21.4 ± 2.2 years, height: 177.2 ± 5.1 cm, body mass: 67.5 ± 5.5 kg) participated in this study. All the participants volunteered for this study and provided informed written consent. This study has been approved by the local Human Subject Ethics Subcommittee (Department of Rehabilitation Sciences, The Hong Kong Polytechnic University).

2.2. Passive stretching

An isokinetic dynamometer was used to impose passive knee flexions (Cybex, Medway, MA, USA). Before the participant was positioned on the dynamometer, the location of the ultrasound transducer was determined on the skin using a waterproof pen for each muscle (VMO: 20% of the distance from the midpoint of medial patella border to anterior superior iliac spine as the test position; RF: 50% of the distance from anterior superior iliac spine to the midpoint of the superior tip of the patella; VL: 1/3 of the distance from the midpoint of lateral patella border to anterior superior iliac spine). Then, participants were positioned supine with their hip flexed at 10° using a customized cushion put on the dynamometer bed to avoid hip hyperextension. The dominant leg, determined by the ball kicking test, was measured. The hip was positioned in a neutral position and the presumed axis of the knee rotation was aligned with the axis of the dynamometer.

2.3. Muscle shear modulus measurements

An Aixplorer ultrasound scanner (Aixplorer Version 4.2; Supersonic Imagine, Aix-en-Provence, France), coupled with a linear transducer (4–15 MHz, Super Linear 15-4; Supersonic Imagine) was used in shear wave elastography mode (MSK preset) to measure the Young's modulus assuming isotropic nature of soft tissues. As skeletal muscle cannot be assumed to be isotropic, we reported the shear modulus values as the Young's modulus values divided by 3.[6]

An experienced examiner performed all the measurements. The transducer was first oriented in the transverse plane to ensure that the right muscle was measured and then rotated to be parallel to the muscle fascicle direction. For VMO and VL, the optimal transducer location was determined when several muscle fascicles could be seen without disconnection through the image.[12] Because of the complex arrangements of RF fascicles, the transducer was placed over the lateral component of this muscle[16–18] and oriented in muscle shortening direction.

The two-dimensional (2-D) maps of muscle shear modulus were captured for 1 sample with a spatial resolution of 1 × 1 mm. Although the size of region of interest (ROI) does not have a significant impact on the shear modulus,[19] the ROI was set as big as possible according to the muscle thickness (about 2.25 cm^2 for VMO and VL, 1.5–2.5 cm^2 for RF) to achieve accurate value of passive tension.

2.4. Experimental protocol

After a 10-min rest period, the participant's quadriceps muscle was passively stretched through slow loading cycles (3°/s) from 0° (full knee extension) to 120° of knee flexion. Before the start of loading cycle, a 5-s rest period was used to optimize the position of the transducer. A self-customized trigger was used to synchronize the Cybex dynamometer and SSI scanner, that is, to start the elastography measurements at the start of the loading cycle. Oral instruction was given to the participants to stay relaxed and avoid any muscle contraction and movement of the leg throughout the passive stretching. The test sequences of the 3 muscles were randomly arranged.

2.5. Data analysis

SSI data were exported in .mp4 format and sequenced in .png. Image processing was performed using a custom Matlab script (MathWorks, Natick, MA, USA). Each image was care-