Introduction
Load sharing among the quadriceps components is involved in all knee functional activities, and inappropriate quadriceps load sharing may be closely related to pathological conditions like patellar malalignment. Biomechanical models have been used to analyze load sharing and optimization has been used to deal with the indeterminate problem (the number of unknown variables like muscle forces exceeds the number of available equations) with various cost functions and constraints. However, it is uncertain whether the cost functions used are actually minimized by the musculoskeletal system and which optimization method is more reasonable. Furthermore, load sharing prediction based on biomechanical modeling is affected substantially (several folds changes) by the muscle parameters used, such as the physiological cross-sectional area, fiber length and composition, pennation angle, insertion and origin sites, moment arm. The purpose of this study was to determine load sharing among the quadriceps components through in vivo experiments on human subjects.

Methods
Five subjects with no prior history of knee injury participated in the study. Informed consent was obtained before the experiment. The subject sat upright with the hip flexed at 85°. The ankle was cast with fiberglass tape and fixed to the distal end of an aluminum beam located on the lateral side of the leg. The proximal end of the beam was mounted onto a six-axis force sensor. The knee was fixed isometrically at 60° flexion.

The vastus medialis (VM), vastus intermedius (VI), rectus femoris (RF), and vastus lateralis (VL) were activated selectively using electrical stimulation. Intramuscular wire electrodes and surface electrodes were used to stimulate the vastus intermedius and other quadriceps components, respectively. Bipolar stimulation was used for surface stimulation because of the improved current flow. The amplitude of the constant current stimulation was varied systematically to activate each of the quadriceps components over a range of contraction levels. Besides the pair of stimulation electrodes, a second pair of electrodes was used for each quadriceps component to record the compound muscle action potential (M-wave). A train of stimulation pulses (0.3 ms pulse width, 25 Hz, and 600 ms train duration) was used to activate each individual quadriceps component and the resulting M-waves and six-axis moments and forces including the knee extension torque were recorded.

Well-controlled voluntary knee extension was then performed by the subjects. A target knee extension torque was displayed on a computer monitor and the subject voluntarily extended the knee under isometric condition to match and track the target torque in real-time. Different levels of contraction were specified for different trials, ranging from 5 to 40% of the maximal extension torque. The same pair of electrodes used to record the M-waves was used to record the voluntarily generated EMG signals. Six-axis moments and forces were also recorded together with the EMG signals.

The relationship between the knee extension torque and the amplitude of the corresponding M-wave, both generated by the same individual quadriceps component, was established over the different contraction levels for each quadriceps component. Since exactly the same electrodes were used to record the M-wave and EMG signals for each muscle, the above torque-M-wave relationship could be used to calibrate the corresponding EMG signal during voluntary contraction. Therefore, the electrode size, shape, material properties, location, inter-electrode distance, skin preparation, amplifier conditions etc. were matched closely between the M-wave and voluntary EMG signals for each quadriceps component, and the uncertainties caused by these factors were minimized.

Results
Significant M-wave was only seen on the quadriceps component that was stimulated, indicating selective activation of the targeted quadriceps component and negligible current overflow (negligible co-contraction of other quadriceps heads).

**References**

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