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Vastus Lateralis Fascicle Length Isometricity at Different Knee Extensor Torques and Angles

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SUMMARY
Muscle fascicle lengths change as a function of muscle length and muscle force. The effect of these two factors may be balanced to maintain the same fascicle length at different joint angles during *in vivo* muscle function. The aim of this study was to determine the relationship between knee flexion angles, knee extensor torques and fascicle lengths of the Vastus Lateralis muscle. We found that a constant fascicle length can be maintained across a range of 60° of knee flexion if knee extensor forces are varied appropriately. Fascicle length isometricity has been found for some functional movements. For example, fascicle lengths in cat [1] and human [2,3] medial gastrocnemius muscles were shown to remain at virtually constant lengths in the mid-stance phase of walking despite substantial changes in joint angles and torques. Fascicle length isometricity may offer important functional advantages in a variety of situations, such as increased force production in "concentric" contractions and savings of metabolic energy [4].

INTRODUCTION
The sarcomere force-length relationship is well established, but in intact fibers and entire muscles, the relationship is complex, involving factors such as sarcomere length non-uniformity and muscle architecture. Most skeletal muscles transmit force to bones by tendons and/or aponeuroses that are primarily comprised of Type-I collagen fibers. Tendons will deform in a characteristic manner when subjected to tensile loading, and this force-elongation relationship can be quantified using constitutive laws.
During an isometric contraction, tension is generated in muscles, transferred to Series Elastic Components (SEC) that deform in a load-dependent manner. As a consequence, muscle fascicle lengths decrease to accommodate the SEC strain and maintain torque generation at joints.
Ito and co-workers [5] determined the torque-angle relationship for human tibialis anterior muscle during isometric contractions at different ankle angles and various percentages of the Maximal Voluntary Contraction (MVC). They found that muscle fibers shortened from a resting length of 87±7 to an activated length of 76±7mm) at a given joint angle, while tendons and other SEC lengthened, thereby maintaining the same total (muscle plus SEC) length. Similar findings have been made by others [6], confirming the intricate relationship between fascicle lengths and force production *in vivo*.
Realizing that fascicle lengths do not only depend on muscles lengths, but also on force, it is possible to change the joint angle, thereby increasing/decreasing muscle-tendon lengths, and increasing/decreasing force in such a way that fascicle lengths remain constant.
The objective of this study was to find a relationship between knee flexion angle and % MVC knee extensor torque for which vastus lateralis (VL) fascicle lengths remain approximately constant. Previous work on VL torque-angle relationships has focused exclusively on changes in shape of this relationship at different levels of contraction, thereby neglecting fascicle isometricities [5].

METHOD
12 subjects (7 male and 5 female) without lower limb injuries gave free informed consent to participate in this study. VL fascicle lengths were measured for eleven contraction levels ranging from 0 to 100% of MVC at 10 % intervals, and for eleven knee angles ranging from 10° and 110° of knee flexion at 10° intervals. Angles and contraction levels were presented in a random order to minimize ordering, fatigue or training effects, and a minimum of a 2 min rest was enforced between contractions.
Isometric knee extensor torques (2kHz) and knee angles were measured using an isokinetic dynamometer (Biodex 3 Pro). Subjects were seated with the hip at a flexion angle of approximately 100°. Subjects were firmly strapped to the dynamometer chair, with the dynamometer axis aligned as closely as possible with the knee rotation centre of the dominant limb. Subjects were asked to build up to the maximal isometric torque at each joint angle slowly, over a period of about 5s, and then hold the maximal torque for approximately another 1-2s. VL fascicle lengths were measured with ultrasound imaging (Phillips HD 11 XE) at about 50% of the thigh length and parallel to the muscle fibers at 10Hz. In order to compare torque-fascicle length relationships across subjects, fascicle lengths were normalized relative to the lengths obtained at maximal knee extensor torque for each subject, and torques were normalized for all subjects to the greatest torque achieved. Note however, that not all subjects had the maximal torque at the same knee flexion angle.

RESULTS AND DISCUSSION
The Torque-Fascicle Length relationship shows the characteristic shift of optimal lengths towards increasing knee flexion angles (longer VL lengths) for decreasing levels of activation (Figure 1). The dashed lines indicate the changes in knee extensor torques as a function of knee angles for a given level of activation, while the solid lines indicate the changes in fascicle lengths with changing activation at a given knee angle. A vertical line in Figure (1) represents a constant

fascicle length across knee angles and activation levels. For example, the shaded vertical line shown represents the optimal fascicle length (100% length) that occurs at the peak of the maximal voluntary contraction curve, but is shifted to increasingly lower levels on the ascending limb of the torque-angle relationship for decreasing levels of activation.

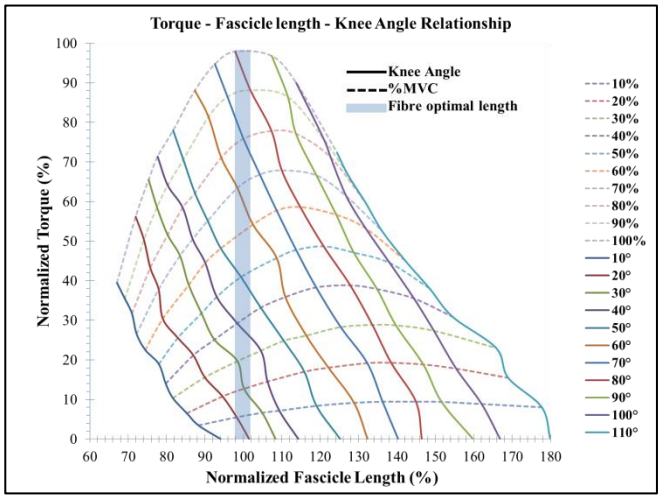

Figure 1: Torque-Fascicle Length-Knee angle relationship for isometric contractions at different levels of activation. Solid lines represent changes in fascicle lengths with changing activation levels at a given knee angle, while the dashed lines represent changes in torque as a function of knee angles for constant levels of activation. The vertical shaded line represents the optimal fascicle length (100% length) of VL across changing knee angles and activation levels.

Figure 2 shows the torque-knee angle relationship for different normalized fascicle lengths. The red squares (and corresponding trend line) represent isometricity at the optimal fascicle length (100% length) for VL. Note that optimal fascicle length is maintained over a range of approximately 60˚ of knee flexion: from 20˚ and 0 activation to 80˚ and maximal activation.

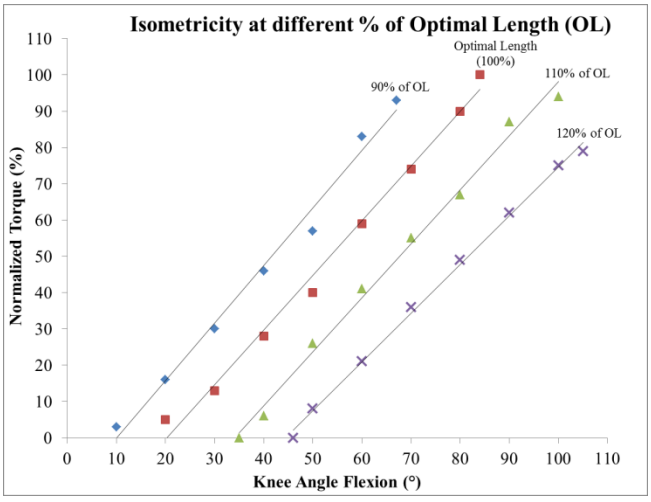

Figure 2. Torque-Knee angle relationship for different Vastus Lateralis fascicle lengths.

Fascicle length isometricity during functional movements have been found for a variety of normal movements: for example for the medial gastrocnemius in mid-stance of level walking in humans [2,3] and cats [1]. This result suggests that force production and length changes in the muscle were such that the resultant fascicle length changes in these dynamic situations were virtually zero [1].

The results found here suggest that isometricity of fascicle length may also occur in human knee extensor muscles for situations where muscle stretch is associated with an increase in force, and muscle shortening with a decrease in force. Such a fascicle length behavior may have several advantages, including that forces for nearly isometric fascicle lengths would be higher than for rapidly shortening fascicle lengths, thus possibly maximizing muscle performance [4], and that energy requirements might be reduced in stretch-shortening cycles [7].

For example, in a counter movement jump, the peak electromyographic activity occurs at the end of the eccentric phase suggesting that the increase in fascicle length associated with muscle lengthening might be partly offset by a shortening of fascicles with increasing force [8].The EMG activity then decreases gradually during the extension phase of jumping, suggesting that the shortening of fascicles with muscle shortening is partly offset by an elongation of fascicles with decreasing force [9].

Another example where our results might have important implications is the so-called Interpolated Twitch Technique (ITT) [4,10]. ITT is a commonly used technique to assess muscle inhibition around normal, diseased and injured joints. Interpolated twitches are typically delivered to a muscle by single twitch stimulations of the corresponding nerve while the muscle is maximally activated and at complete rest. The increase in force at the maximal activation is then taken as the untapped force during voluntary contraction, and is quantified by comparing it to the resting twitch force magnitude which theoretically shows the full twitch force potential of the muscle at rest. However, when delivering the interpolated twitch to a muscle at rest and while fully activated, the fascicle lengths are substantially different, thus potentially confounding the results by where on the force-length relationship the fibres are while the twitch is given.

CONCLUSIONS

VL fascicle lengths change as a function of knee angles (muscle lengths) and knee extensor torques (VL muscle force). Isometricity of VL fascicle lengths can be achieved over a surprisingly large range of knee angles if activation is changed appropriately. These results may have important, and as of yet neglected, implications for human knee extensors during dynamic movements.

ACKNOWLEDGEMENTS

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