In vivo estimation of contraction velocity of human vastus lateralis muscle during "isokinetic" action

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Ichinose, Y., Y. Kawakami, M. Ito, H. Kanehisa, and T. Fukunaga. In vivo estimation of contraction velocity of human vastus lateralis muscle during "isokinetic" action. J. Appl. Physiol. 88: 851–856, 2000.—To determine the shortening velocities of fascicles of the vastus lateralis muscle (VL) during isokinetic knee extension, six male subjects were requested to extend the knee with maximal effort at angular velocities of 30 and 150°/s. By using an ultrasonic apparatus, longitudinal images of the VL were produced every 30 ms during knee extension, and the fascicle length and angle of pennation were obtained from these images. The shortening fascicle length with extension of the knee (from 98 to 13° of knee angle; full extension = 0°) was greater (43 mm) at 30°/s than at 150°/s (35 mm). Even when the angular velocity remained constant during the isokinetic range of motion, the fascicle velocity was found to change from 39 to 77 mm/s at 150°/s and from 6 to 19 mm/s at 30°/s. The force exerted by a fascicle changed with the length of the fascicle at changing angular velocities. The peak values of fascicle force and velocity were observed at ~90 mm of fascicle length. In conclusion, even if the angular velocity of knee extension is kept constant, the shortening velocity of a fascicle is dependent on the force applied to the muscle-tendon complex, and the phenomenon is considered to be caused mainly by the elongation of the elastic element (tendinous tissue).

isokinetic knee extension; fascicle shortening velocity; force-velocity relationship

The force-velocity relationship in human skeletal muscle has been studied by methods such as inertial loading (10) and "isokinetic" loading (3, 4, 14, 15, 19, 21). Isokinetic instruments (e.g., Cybex) have been widely used for measurement of human muscle function in various research fields such as sports science and rehabilitation. However, the force-velocity relationship determined with an isokinetic machine has been shown to deviate from Hill’s equation. For example, Perrine and Edgerton (15) reported that the joint torque produced at a low angular velocity in isokinetic extension of the knee was lower than that approximated by Hill, i.e., their isometric torque was 4% lower at 96°/s. They considered neural inhibition as a factor in these differences. Also, according to the results of Fuglevand (4), the torque-angular velocity-joint angle relationship in humans was in fact different from the

force-length-velocity relationship reported earlier in isolated muscles. There were, however, no concrete data that explained these differences because the length or velocity of the muscle could not be estimated in vivo in human joints so far.

Torque has often been obtained with an isokinetic instrument either as the maximum value in the torque curve (peak torque) or as the torque at a particular angle (angle-specific torque). The joint angle at which the peak torque was observed was found to shift distally in the range of motion as the angular velocity increases (4). Therefore, peak torque must be measured and compared at different muscle lengths (21). Evaluation of angle-specific torque is theoretically based on the measurement of torque at the same muscle length (21). In both cases, the “muscle length” represents the length of the muscle-tendon complex inclusive of the tendon as a series elastic component rather than the length of the contractile component per se. Some researchers (15, 21) have assumed that changes in the joint angle are equivalent to changes in the muscle length and to changes in the length of muscle fibers. However, Fukunaga et al. (6) demonstrated that during knee extension in humans the tendon was stretched by the tension applied to it and that the length of muscle-tendon complex was not equal to the length of muscle fibers (fascicles). Therefore, when the force-velocity relationship of the muscle is measured in vivo by applying an isokinetic loading system to a human joint, the contraction velocity of the muscle does not appear to be uniform even if the joint angular velocity remains constant. Given this finding, the purpose of the present study is 1) to determine the velocity of contraction of the muscle fiber (fascicle) during maximum isokinetic extension of the knee and 2) to examine the force-velocity relationship at work in fascicles.

METHODS

Six male volunteers were engaged as subjects (age 24.3 ± 0.7 years; height 172.8 ± 1.9 cm; weight 74.3 ± 2.8 kg; means ± SD). Informed consent was obtained from each subject before the experiments.

The torque produced in knee extension was measured by an isokinetic loading instrument (MYOLET, ASICS). During measurement, the subjects were seated with hip joints flexed at 80° (full extension = 0°). Shoulders and abdomen were fastened with belts, and the right leg was strapped above the ankle to the lever arm of the loading instrument. Attention was paid to keeping the center of the knee in line with the axis of the lever arm. Gravity was compensated for by placing the lever arm as close to a horizontal position as possible and

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having the subject relax the leg, thus obtaining net torque by subtracting the weight of the attachment from the torque exerted by the subject on the loading machine.

The peak "isometric" torque measurements were performed randomly in the order of 70, 60, 80, and 30°. After warming up at submaximum exertion, subjects performed two maximum isometric leg extensions at each knee joint angle, and the higher value of the two trials was adopted. To eliminate the effect of fatigue, trials were performed at intervals of 2 min or longer.

After measurement of the maximum isometric torque (at a given angle of the joint), a 3-min rest was taken, and the isokinetic torque was measured at the angular velocities of 30 and 150°/s. The range of motion of the knee was 110° flexion to complete extension (0°). At sudden maximum exertion from rest or from a very low level of isometric muscle activity, the changes in both torque and contraction velocity of the muscle before joint peak torque have previously been reported to be affected by the slackness of muscle-tendon complex (2). In the present study, too, it was important to eliminate slack from the muscle-tendon complex at rest to ensure direct transmission of the force of muscle fibers to the joint. Therefore, the torque at maximum isokinetic extension of the knee was measured immediately following a 2-s maximum-effort isometric knee extension at a knee joint angle of 110°. To allow the subjects to become accustomed to the conditions of measurement, three to four practice trials were first conducted at submaximum exertion at each velocity, followed by at least three trials at maximum effort. The trials were spaced at intervals of 1–2 min. The greatest torque value measured was adopted as the peak torque.

The fascicle length and pennation angle of the vastus lateralis muscle (VL) of the right thigh were measured with a B-mode ultrasound instrument (SSD-2000, Aloka), as previously measured by Fukunaga et al. (5, 6). The width of the VL was measured at 50% of the length of the thigh, and the center of the width was marked. An ultrasonic probe with a frequency of 5 MHz and a scanning area of 8 cm was used to observe the fascicles and aponeurosis. The probe was gently attached to the skin of the femoral region with surgical tape so as not to compress the tissue, and it was supported by the examiner's hand so that images of the uniform longitudinal plane of the tissue might be obtained. The probe was applied while the subjects performed leg extensions with maximum effort, and the examiner made sure that accurate images could be obtained throughout the range of motion. The ultrasound images were recorded as video signals at 30 Hz, and the video recorder (HR-V, Victor) and were synchronized with the torque and joint-angle data by superimposing the clock timer.

To obtain the fascicle length and the pennation angle, the ultrasound images recorded with the video recorder were printed out every 30 ms, the fascicles were traced in these images, and fascicle length and pennation angle were determined using a digital curvimeter (Concurve8, Koizumisokki). Changes of fascicle length were measured over the entire range of motion at various points, and the contraction velocity of fascicles was determined at those points. Fascicle length was measured within a range of knee joint angles of 100–10°, and the means of the six subjects were calculated at every 5°. The mean fascicle velocity was calculated over a range of knee joint angles corresponding to the isovelocity period of angular velocity (i.e., 80–20°).

The force acting on the tendon of the quadriceps muscle (tendon force) was calculated by dividing the torque measured at each knee joint angle by the moment arm. The moment arm values reported by Marshall et al. (14) were utilized in this calculation. Since the moment arm changes with the knee joint angle, the values read from Fig. 4 of Marshall et al. (14) were regressed against the knee joint angle through use of a quadratic equation, and the moment arm at each knee joint angle (every 5°) was obtained. Then, the same moment arm values were used for all subjects. The VL force in the direction of the fascicle (fascicle force) was calculated by using the following equation, on the assumption that physiological cross-sectional area (PCSA) represented the force exerted by the muscle

\[ F_{t} = \frac{TQ}{\text{moment arm}} \]

where \( F_{t} \) is the tendon force, \( TQ \) is the knee extension torque, \( F_{t} \) is the fascicle force, \( K \) is the relative PCSA of VL to the total PCSA of the quadriceps femoris (= 34%; reported by Akima et al. (1)), and \( A_{p} \) is the pennation angle.

**RESULTS**

Figure 1 shows typical ultrasonic images from the vastus lateralis muscle during maximum isokinetic knee extension at 150°/s and 30°/s for two given knee joint angles (10° and 100°). The shortening of fascicle length with extension of the knee was more pronounced at 30°/s than at 150°/s (Fig. 2). Immediately after the beginning of the exercise (i.e., at 100° of knee joint angle), fascicle lengths were 105 mm and 108 mm at 30 and 150°/s, respectively. With extension of the knee, fascicle length was shortened by 43 mm (40%) to 62 mm at 30°/s and by 35 mm (31%) to 73 mm at 150°/s.

Although the angular velocity (Fig. 3, A and C) appeared constant in isokinetic knee extension from 88 to 100° of knee joint angle (isokinetic range of motion), the fascicle velocity changed remarkably (Fig. 3, B and D). A shortening of fascicle velocity from 39 to 77 mm/s (50%) at 150°/s and from 6 to 19 mm/s (30%) at 30°/s was noted. The knee joint angle of peak fascicle velocity was observed at the more extended position of 57° at 150°/s, compared with 71° at 30°/s. The mean fascicle length was resolved as length of line drawn along ultrasonic echo parallel to fascicles. Fascicle angle was determined as angle between fascicles and deep aponeurosis.

**Fig. 1.** Examples of ultrasonic images of vastus lateralis muscle (VL). Images were obtained at 50% of thigh length. Left: knee joint angle of 10° at an angular velocity of 150°/s. Right: knee joint angle of 100° at an angular velocity of 30°/s. High-contrast echo at top of view indicates border between subcutaneous adipose tissue and muscle and near bottom represents a deep aponeurosis.
velocity in the isokinetic range of motion was 61 mm/s at 150°/s, about four times larger than the value of 15 mm/s at 30°/s, but this difference was in fact smaller than that observed in angular velocity (5 times).

Figure 4 shows the changes in peak torque and in angle-specific torque at a 30° knee joint angle as a function of angular velocity. The torque-angular velocity relationship in angle-specific torque at a 30° knee joint angle turned out to be relatively flat compared with peak torque, and the angle-specific torque at a 30° knee joint angle recorded at each angular velocity was as much as 55–65% that of peak torque. During knee extension exercises, joint torque changed with knee joint angle, i.e., peak torque was observed at the less extended position of 30°/s (65°) rather than at 150°/s (52°), the corresponding torque values being estimated at 220 and 149 N·m, respectively.

During knee extension, the $F_f$ was noted to change with increasing fascicle length at either angular velocity (Fig. 5). The maximum values of the $F_f$, 1,870 N at 30°/s and 1,107 N at 150°/s, were observed at 90 mm fascicle length, after which $F_f$ tended to decrease rapidly.

Figure 6 shows changes in fascicle velocity due to fascicle length. Concerning the relationship between fascicle velocity and knee joint angle, the knee joint angle observed at peak fascicle velocity showed variance with angular velocity. However, peak fascicle velocity (72 mm/s at 150°/s and 20 mm/s at 30°/s, respectively) was observed at ~90 mm fascicle length at either angular velocity, at the same position where peak $F_f$ was obtained in Fig. 5.

The $F_f$-fascicle velocity relationships are shown in Fig. 7. The lines in the figure connect the values at a given fascicle length (optimal fascicle length = 90 mm) where $F_f$ peaked in trials at 30 and 150°/s. The $F_f$ decreased by 37% (from 3,000 N at isometric to 1,119 N at 70 mm/s of fascicle velocity) with increasing fascicle velocity.
DISCUSSION

Although fascicle length has already been known to change with knee joint angle during static contraction and even at rest (6), fascicle length was found to decrease in the present study by as much as 60–67% with knee extension at either angular velocity, 30°/s and 150°/s, respectively. In previous studies (15, 21), dynamic torque during knee extension has been often measured at a knee joint angle of 30°, where relative fiber length has been found to be the same. In our study, however, given the same knee joint angle of 30°, fascicle length was shorter by 15% during contraction at 30°/s (68 mm) than during contraction at 150°/s (80 mm). Consequently, the length of the contractile component differed markedly with angular velocity even at the same joint angle, which has hitherto been assumed to be affected by the length change of the elastic component due to the force (or velocity) exerted on the muscle-tendon complex. In our view then, the hypothesis that changes in the joint angle equal changes in fascicle length is clearly invalidated.

Furthermore, earlier research has suggested that the velocity of muscle-tendon complex is constant if angular velocity is fixed. However, our study showed that fascicle velocity changed over the entire range of motion and that the difference in mean fascicle velocity for either value of angular velocity was lower (4 times) than the difference in angular velocity (5 times). Moreover, the relationship between the knee joint angle and fascicle length differed with angular velocity. Major factors that cause these differences are thought to include 1) moment arm, 2) pennation angle, 3) elastic components, and 4) excitation level of the nervous system.

First, changes in the moment arm associated with changes in the knee joint angle are considered to affect changes in the length of the muscle-tendon complex (8, 14, 16, 17). Because the moment arm of a joint differs with the knee joint angle, the contraction velocity of the muscle-tendon complex is not constant even when the joint angular velocity is unchanged. According to the values of Marshall et al. (14), which were used in the present study, the moment arm approached maximum at near 40° knee joint angle. As the moment arm increases, the change in the length of the muscle-tendon complex becomes greater, too, together with changes in fascicle length, even when the change in the knee joint angle is the same. Interestingly, however, the knee joint angle at which the moment arm reached maximum was found to be different from the angle at

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Fig. 5. Relationship between fascicle length and VL force in direction of fascicle at either angular velocity. Maximum values of VL force were observed at 90 mm of fascicle length at either angular velocity.

Fig. 6. Relationship between fascicle length and fascicle velocity. Peak fascicle velocity was observed at 90 mm of fascicle length at either angular velocity.

Fig. 7. Relationship between fascicle velocity and fascicle force ($F_f$). Plots represent $F_f$-fascicle velocity relationships at 0°/s ($\bullet$), 30°/s ($\blacksquare$), and 150°/s ($\circ$), respectively. Lines connect same fascicle length values at optimal length (90 mm) at maximum voluntary contraction in trials at 30 and 150°/s. Optimal fascicle length was observed at knee joint angles of 73° at 30°/s and of 47° at 150°/s, respectively, and it appeared at a more extended knee joint position as angular velocity was faster.
which fascicle velocity was maximum at 57–71°, given any angular velocity. These results indicate the presence of factors that affect changes in fascicle velocity in addition to changes in the moment arm.

Second, the pennation angle will be discussed. The relation between fascicle length and length of muscle-tendon complex was affected by pennation angle, which changes with the knee joint angle and the activation level (6). When the knee was extended, length of muscle-tendon complex and fascicle length were reported to be shortened, and pennation angle increased (6). In our study, when the knee was extended with maximum effort, pennation angle increased from 15° to 25° in step with changes in the knee joint angle. The pennation angle affects the percentage of the shortening of the fascicle transmitted toward the tendon (22).

However, as the relationship between changes in all lengths of muscle-tendon complex, knee joint angle, and fascicle lengths is expressed by

$$\Delta L_{\text{mtc}} = \Delta L_{f} \cdot \cos A_{p}$$

where $\Delta L_{\text{mtc}}$ is muscle length change, $\Delta L_{f}$ is fascicle length change, and $A_{p}$ is the pennation angle, it follows that a change in $\Delta L_{\text{mtc}}$ with a pennation angle of 13–25° is small (its cosine component being 0.97–0.91). Therefore, the effect of pennation angle on the relationship between length of muscle-tendon complex and fascicle length is considered to be nearly negligible.

Third, effects of elastic components such as the tendon and aponeurosis will be considered. The difference in fascicle velocity shortening observed between the two angular velocities in this study was noted to be smaller than the difference between the joint angular velocities themselves, presumably because a greater force was produced at 30°/s with the same range of motion, causing greater extension of the tendon and hence greater shortening of the fascicle. If the tendinous tissue is assumed to be very firm and does not change in length, the range of motion would be the same at 150 and 30°/s, and changes in $L_{\text{mtc}}$ and fascicle length would be identical, too. In a previous study based on the gastrocnemius muscle of the rat (23), the velocity of shortening of muscle fibers was found to be slower than the velocity of shortening of the muscle-tendon complex at all muscle lengths, and the ratio of these two variables also varied with the length of the muscle-tendon complex. This ratio has been reported to be affected by changes in the length of the aponeurosis associated with changes in tension. The strain of the aponeurosis in the animal muscle varied at 14.3% (24), 8% (13), and −2% (13). Elsewhere, research indicated that change in the ratio of tendon length to muscle fiber length was dependent on a force exerted by muscle tissue (20). All these reports recommended taking into consideration the effect of elastic components in the evaluation of the mechanical characteristics of muscle-tendon complex.

Lastly, factors of the nervous system will be evaluated. It has been suggested that the excitation level of the muscle during maximum isokinetic exercise was the same even when angular velocity varied (4, 15, 21). However, Bobbert and Harlaar (2) demonstrated in electromyogram records from the extensor muscle of the knee that the excitation level of the muscle does vary with the angular velocity of the joint and was not fixed throughout the range of motion. The authors reported that the excitation level of the muscle was nearly the same as that at maximum voluntary contraction over the entire range of motion at 30°/s. Detailed discussion about the activity level of the muscle is not possible, because we did not record electromyogram values in the present study. The excitation level of the muscle may in fact be relatively constant although it does seem to be affected by acceleration in the proximal part of the range of motion and by deceleration in the distal part of the range of motion.

The shape of our angular velocity-peak torque curve was similar to that of the force-velocity curve estimated by Hill’s specific formula, and the values of the torque exerted there were similar to those found in earlier reports (3). On the other hand, in our experiments, the curve of angular velocity vs. angle-specific torque at a 30° knee joint angle appeared flatter than the angular velocity-peak torque curve. According to reports to date (3, 15, 18, 21), the peak of the curve for angular velocity vs. angle-specific torque at a 30° knee joint angle has been noted at 30–60°/s by some researchers but at 0°/s by others (7, 11), the findings in fact being inconsistent. In the case of the angular velocity-peak torque curve, too, the peak has been reported at 30–60°/s by some authors (3) but at 0°/s by others (10, 19).

In Fig. 7, the force-velocity relationship at a fixed fascicle length (90 mm optimal length) resembles the angular velocity-peak torque relationship. These curves also more closely reflect the force-velocity relationship in the isolated animal muscle than the curve obtained using angle-specific torque. Angle-specific torque has been used frequently in earlier studies for comparison of the force-velocity relationship at a fixed muscle length (15, 21). However, as shown in the present study, the same fascicle (muscle fiber) length cannot be obtained by fixing the angle, so it appears that the method used in previous studies has not met the objective. However, as shown in Fig. 7, the torque at 30 and 150°/s was close to peak when the fascicle length was equal to optimal fascicle length (90 mm), at which point maximum tension, i.e., optimal length, was observed. This finding suggests that the peak torque is more appropriate than the angle-specific torque for the estimation of contraction characteristics of the muscle in joint motions (knee extension).

In our study, analysis was based only on the VL, but the torque of knee extension is in fact the sum of the forces produced by the other quadriceps muscles of the thigh (rectus femoris, vastus medialis, and vastus intermedius) as well as the VL. Lieb and Perry (12) reported that the VL makes the greatest contribution to the force produced by the quadriceps muscle of the thigh from 90° flexion to 0° extension but that the degree of contribution by each muscle to knee extension varies with the knee joint angle. Especially, as the degree of contribution of the vastus medialis muscle
increases in the extended position, it may not be appropriate to make a connection between the torque near the extended position and changes in fascicle length of the VL based on the assumption that the force being applied to fascicles and tendon is 1:1. In fact, the torque produced appeared equal at different fascicle lengths, but fascicle length diverged notably near the extended knee position at different angular velocities, possibly because of the effect of differences in the degree of contribution of these synergistic muscles.

In conclusion, the velocity of shortening of fascicles changed even during isokinetic exercise, and the effects of the moment arm, pennation angle, series elastic component, and excitation level were all considered to be involved in these changes. Furthermore, although the force-velocity relationship has been frequently analyzed in terms of the angle-specific torque in in vivo studies, the results of our study suggest that the peak torque more accurately reflects the actual force-velocity relationship in the muscle fiber.

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