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published in
Medicine and Science in Sports and Exercise
2006

DOI (link to publisher)
10.1249/01.mss.0000227644.14102.50

citation for published version (APA)
de Ruiter, C. J., Leeuwen, D., Heijblom, A., Bobbert, M. F., & de Haan, A. (2006). Fast unilateral isometric knee extension torque development and bilateral jump height. *Medicine and Science in Sports and Exercise*, *38*, 1843-52. https://doi.org/10.1249/01.mss.0000227644.14102.50

Fast Unilateral Isometric Knee Extension Torque Development and Bilateral Jump Height

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ABSTRACT

DE RUITER, C. J., D. VAN LEEUWEN, A. HEIJBLOM, M. F. BOBBERT, and A. DE HAAN. Fast Unilateral Isometric Knee Extension Torque Development and Bilateral Jump Height. *Med. Sci. Sports Exerc.*, Vol. 38, No. 10, pp. 1843–1852, 2006. **Purpose:** We hypothesized that the initial rate (first 40 ms) of unilateral knee extensor torque development during a maximally fast isometric contraction would depend on the subjects' ability for fast neural activation and that it would predict bilateral jumping performance. **Methods:** Nine males (21.8 ± 0.9 yr, means ± SD) performed unilateral fast isometric knee extensions (120° knee angle) without countermovement on a dynamometer and bilateral squat jumps (SJ) and countermovement jumps (CMJ) starting from 90 and 120° knee angles (full extension = 180°). The dynamometer contractions started either from full relaxation or from an isometric pre-tension (15% maximal isometric torque, Tmax). Torque time integral for the first 40 ms after torque onset (TTI-40, normalized to Tmax) and averaged normalized rectified knee extensor EMG for 40 ms before fast torque onset (EMG-40) were used to quantify initial torque rise and voluntary muscle activation. **Results:** TTI-40 without pre-tension (range: 0.02–0.19% Tmax per second) was significantly lower than TTI-40 with pre-tension, and both were significantly ($r = 0.81$ and 0.80) related to EMG-40. During jumping, similar significant positive relations were found between jump height and knee extensor EMG during the first 100 ms of the rise in ground reaction force. There also were significant positive linear relations between dynamometer TTI-40 and jump height ($r = 0.75$ (SJ 90), 0.84 (SJ 120), 0.76 (CMJ 90), and 0.86 (CMJ 120)) but not between dynamometer Tmax and jump height ($-0.16 < r < 0.02$). **Conclusion:** One-legged TTI-40 to a large extent explained the variation in jump height. The ability to produce a high efferent neural drive before muscle contraction seemed to dominate performance in both the simple single-joint isometric task and the complex multijoint dynamic task. **Key Words:** HUMAN, VOLUNTARY MUSCLE ACTIVATION, EMG, TORQUE RISE

The rate of skeletal muscle force development depends greatly on neural activation of the muscle fibers at the start of a contraction (14): a faster increase of the free intracellular [Ca2+] will allow the fraction of bound cross-bridges to increase at greater rate and force to develop at a faster rate. The maximal rate of force development can only be reached at a very high level of muscle activation. To obtain the maximal rate of force development, more action potentials per time unit have to reach the muscle fibers than are necessary for the production of maximal isometric force (2,12,18,29). During maximally fast voluntary contractions, neural activation seems to determine the extent to which the muscle fibers' potential for force development can be used. Indeed, it has recently been shown in young healthy subjects that the intersubject variation in capacity for fast neural activation (defined as the ability to produce high initial EMG peaks at the start of a contraction) of the knee extensors accounted for 76% of the variance found in the torque time integral (TTI) for the initial 40 ms (TTI-40) of fast voluntary isometric torque development (14). The capacity for fast neural activation may be important for *in vivo* motor function because during balance corrections and fast powerful tasks such as jumping, the time to build up muscle torque is limited to 200 ms at the most (21). Consequently, performance on these tasks is expected to benefit from faster neural activation, which will lead to faster torque development and, consequently, the production of higher peak torques in the limited time available.

Thus far, various measures of the rate of isometric torque development as measured on a dynamometer have been found to be unrelated (6,15,22) or only moderately related (24,31) to maximum jump height. There are several possible explanations to account for the poor relationships reported in previous investigations. First, there are points of concern with respect to the reliability of the used measures of torque development and jump height, the stiffness of the dynamometer, the stiffness of the interface between subject and

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Submitted for publication December 2005.
Accepted for publication May 2006.

0195-9131/06/3810-1843/0
MEDICINE & SCIENCE IN SPORTS & EXERCISE®

DOI: 10.1249/01.mss.0000227644.14102.50

testing apparatus, and standardization of jump execution. For example, in most of the above studies, joint angles at the start of jumping were not carefully controlled. Moreover, previous studies have not focused on the very initial phase of dynamometer torque development. Recently, it has been shown that the intersubject variation in this parameter may depend more on neural activation than on differences in the intrinsic contractile speed of the muscle fibers (14), although intrinsic contractile speed is also important at the very start of torque development (4). Secondly, and alternatively, the predictability of jump performance based on a measure of isometric torque development of a single muscle group may be truly poor because jumping requires the use of various muscle groups, nonisometric contractions, and a more complex coordination; hence, it has been suggested that a test of isometric performance may not be movement specific enough to predict jump height (6,28).

The present study is the first to focus on the very initial phase of isometric torque development in relation to jump performance. Torque rise during this very initial phase of isometric torque development has recently been shown to depend predominantly on the capacity for fast neural activation (14). In the present study, we assumed that the ability for fast neural activation is a more general, subject-dependent ability rather than a highly task-specific ability. Therefore, we hypothesized that subjects with a fast initial phase of one-legged single-joint isometric torque development (higher TTI-40) would jump higher than subjects with a slow initial phase, despite the obvious differences in complexity between both tasks. Thus, under carefully controlled experimental conditions and using a sensitive and reliable (intraclass correlation coefficient of 0.95) new (2,14) measure of the rate of isometric torque development, significant positive relations were expected between maximally fast (one legged) voluntary isometric torque development and maximal (two legged) jump height. Moreover, with more extended knees at the start of a jump, the time for muscle activation would be further restricted by the shorter duration of push-off. Consequently, the relation between jump height and TTI-40 was expected to be stronger when jumps started from a 120° knee angle (full extension = 180°) than when jumps started from a 90° knee angle.

METHODS

Subjects

The local ethics committee approved the study. Nine healthy male subjects (Table 1) signed informed consent and came to our lab twice with at least 2 d in between. The subjects participated in sports at a recreational level. High-level athletes of (inter)national caliber and athletes who were highly trained for endurance (e.g., long-distance runners) or power events (sprinters, weight lifters) were excluded from participation in the present study to minimize the effects of differences in muscle fiber-type composition and specific training. On the first day, they were familiarized with the procedures and with the electrical stimulation. In addition, they practiced to perform maximally fast one-legged isometric knee extensions, without exerting any preflexion or preextension torque, at a 120° knee angle (complete knee extension = 180°). Moreover, voluntary activation at the plateau of a maximal voluntary contraction (MVC) was determined using superimposed electrical stimulation (see below). In addition, the subjects practiced jumping from a 90 and 120° squat position with and without a preceding countermovement. Total duration of the practice session was 2 h. The actual data collection was done on the second day.

TABLE 1. Subject characteristics.

Subject	Height (m)	Weight (kg)	Age (yr)	Knee Extension MVC (N·m)	Sport (h·wk^{-1})
1	1.80	86.1	22.2	319	Gymnastics/indoor soccer (2)
2	1.90	67.1	20.7	305	Soccer (2)
3	1.78	71.0	21.4	235	Indoor soccer (3)
4	1.75	73.8	23.0	247	Soccer/tennis (10)
5	1.82	75.0	22.4	332	Soccer (6)
6	1.72	75.9	21.8	222	Middle-distance running (6)
7	1.78	71.2	23.0	327	Triple jump (8)
8	1.97	78.6	20.8	316	Speed skating (10)
9	1.78	69.1	20.8	263	Indoor soccer (2)
Mean	1.81	74.2	21.8	285	(5.4)
SD	0.08	5.7	0.9	43	(3.4)

Isometric Torque Measurement

Contractile properties of the knee extensors of the dominant leg were investigated using a custom-made dynamometer (Fig. 1). Subjects sat in a backward-inclined (15°) chair, with a 100° hip angle. They were firmly secured with straps fastening hips and shoulders. The lower leg was tightly strapped to a strain gauge transducer (KAP, E/200Hz, Bienfait B.V. Haarlem, The Netherlands) placed 27 cm distally from the knee joint, which measured the force exerted at the shin. The real-time force, corrected for gravity, applied to the force transducer was displayed online on a computer monitor and digitally stored (2 kHz). Measurements were done at the 120° knee angle (which was set manually using a goniometer and using as reference landmarks the greater trochanter, the lateral epicondyle, and the lateral malleolus) while subjects exerted a force of about 50% MVC. For more details about this procedure, see de Ruiter et al. (14).

To ensure high stiffness between shin and aluminium transducer while avoiding pain, the interface only consisted of a standard hard shin protector as used during soccer. Before every muscle contraction, the upper leg was firmly strapped down to the seat just above the knee, and this strap was released between contractions. The axis of rotation of the knee was aligned with the axis of rotation of the dynamometer. The stiffness of the dynamometer arm at the position of the transducer was very high: 7143 N·m·deg^{-1}. Despite these measures, an unavoidable 3–7° increase in knee angles, attributable to soft-tissue compression, always occurred when the knee extensor torque increased from zero to maximal values (14).

[redacted]

FIGURE 1—The custom-made ergometer.

Electrical Stimulation

To limit the duration of the experiments on the second day, electrical stimulation was only applied during the first day (familiarization day). Constant-current electrical stimulation (100-μs pulses) was applied using a computer-controlled stimulator (model DS7H, Digitimer Ltd., Welwyn Garden City, UK) and a pair of self-adhesive surface electrodes (Schwa-medico, The Netherlands). Following shaving of the skin, the cathode (5 × 5 cm) was placed in the femoral triangle above the femoral nerve, and the anode was placed transversely over the gluteal fold. At the start of the session, stimulation current was increased until force in response to a burst of three pulses applied at 300 Hz (triplet) leveled off. The latter always occurred between 300 and 500 mA, and it was assumed that at that point all of the knee extensor muscle fibers were fully activated.

To calculate voluntary activation (VA) at the plateau of an MVC, triplet stimulation on the relaxed knee extensor muscles followed by triplet stimulation superimposed at the plateau of an MVC was performed twice. VA = 1 − (triplet amplitude at MVC/triplet amplitude at resting muscle) × 100% (7,13,27).

If force had changed by more than 1% during the 100 ms prior to the superimposition of the triplet, the attempt was discarded and an additional attempt was made. If necessary, the timing of the superimposed triplet, which was set at an individually adjusted time (usually 1.5–3.0 s after torque onset) before each attempt, was adjusted. Voluntary activation was determined to check the extent to which the obtained MVC was a good representation of the maximal force-generating potential of the knee extensors under conditions of maximal (electrical) activation.

Surface Electromyography

Surface electromyograms were recorded of the following muscles of the dominant leg: vastus medialis, rectus femoris, vastus lateralis, long head of the biceps femoris, and semitendinosus. A portable EMG unit, model Porti5 (TMS int., Enschede, The Netherlands), was used. EMG signals were sampled at 2000 Hz, and low-pass (hardware) filtered at 540 Hz before storage on computer disc. After shaving, cleaning with 70% ethanol, and roughening of the skin, Ag/AgCl surface electrodes (ø 11.5 mm, Blue Sensor N , Ambu A/S, Ballerup, Denmark) were placed in a bipolar configuration parallel to muscle fiber direction, with an interelectrode distance of 20 mm at the distal third of the muscles. A reference electrode was placed on the right medial epicondyle of the femur.

EMG signals were corrected for offset, filtered using a unidirectional zero-phase-lag high-pass (5 Hz) second-order Butterworth filter, and rectified. EMG signals were normalized as follows. For each muscle, EMG averaged over 100 ms before the instant that the highest voluntary torque at the plateau of MVC was produced was taken as 100%.

Kinematics and Dynamics

During jumping, ground reaction forces (GRF) were recorded at 200 Hz using a force plate (Kistler, type 9281, Kistler Instruments Corp., Amherst, NY) connected to an eight-channel charge amplifier (Kistler, type 5053 A 351). Force data collection was controlled by custom-designed software, and data were stored for offline analysis. Kinematics were obtained at 200 Hz using a 3D camera system (Optotrak, type 3020, Northern Digital inc., Waterloo, ON, Canada). To define body segment orientation, six markers were placed on the following anatomical landmarks on the right side of the body: the lateral side of the calcaneus, the fifth metatarsophalangeal joint, the lateral malleolus, the ateral condyle of the tibia, the greater trochanter of the femur, and the neck at the lateral projection of the fifth cervical vertebra. All position data were filtered bidirectionally using a fourth-order low-pass Butterworth filter with a cutoff frequency of 8 Hz. From the 3D coordinates, segment lengths and joint angles were calculated. Linear velocities and acceleration of the markers and angular velocities and acceleration of the segments were calculated using a numeric differentiator (custom-written software). Jump height was defined as the difference in hip marker position at the highest point of the jump and the height in upright standing position. To take differences in body mass among the subjects into account, the change in potential energy of the subjects was used as a second parameter for jump capacity. It was defined as the difference in vertical hip marker position at the highest point of the jump and the instant subjects lost ground contact at the end of the push-off (h) multiplied by body weight (m) and gravitational acceleration (*g*).

Experimental Protocol

The markers and EMG electrodes were placed at the beginning of the experiment. Cables were taped to the skin, and the subjects wore a tight short to further reduce cable movements. On the force plate, body mass and the orientation of the Optotrak markers in standing position were determined. The vertical jump tests were performed first so that the Optotrak markers could be removed after jumping, thereby reducing the amount of cables attached to the subject.

Vertical jump. All jumps were performed with both hands gripped together behind the back and with the trunk as straight as possible. As a warm-up, subjects performed 12 jumps: countermovement jumps (CMJ) and squat jumps (SJ) from 120 and 90° knee angles (three CMJ 90, three SJ 90, three CMJ 120, and three SJ 120). During the subsequent tests, the subjects also jumped from their preferred knee angle. The latter jumps were included because we initially were afraid that imposing a knee angle could be detrimental for jump performance. The three sets of knee angles (90°, 120°, and preferred) were tested in random order. Rest between consecutive jumps in a set was 1 min, and between the sets there were 2 min of rest. In each of the three sets, at least three approved (see criteria below) jumps had to be made. If the last jump was more than 5% higher than the highest previous jump, an additional jump was made. A SJ was rejected when a countermovement of the center of body mass larger than 1.5 cm had been made. This seemed reasonable because it is very difficult to perform a SJ with zero countermovement. Moreover, it has been reported that a countermovement of small (1–3 cm) amplitude does not increase maximal jump height significantly (19).

Each set of jumps started with a CMJ. In this manner the subjects could, at the start of the subsequent SJ, be placed in exactly the same body position as they had attained at the deepest point during their best preceding CMJ. This allowed for the best comparison between SJ and CMJ performance. The reason for including both SJ and CMJ was that although the execution of a SJ can be better standardized among subjects, the CMJ may be regarded as a more natural way of jumping.

With CMJ from the 90 and 120° knee angle, subjects were first positioned in the target knee angle (90 or 120°) that had to be attained at the deepest position to get a feeling for the intended depth of the following jump. This was feasible because knee angle information from the camera system was available online. Immediately after this positioning procedure, the subject rose and started, at will, the CMJ from the upright position. A CMJ was rejected if the knee angle at the deepest point in the jump deviated more than 5° from the 90 or 120° knee angle.

In each set, after the CMJ, SJ were performed that started from the deepest knee angle attained in the highest preceding CMJ. The body segment orientation at that point of the jump was presented as a sagittal-plane stick figure on a computer screen. The subject's current body configuration was also presented on the screen. At the start of the SJ, the subject had to match his current body position with the one of the preceding CMJ depicted on the screen.

During the jumps made from the preferred position, knee angle at the deepest point and jump height turned out to be not significantly different from those obtained during jumps from the 90° knee angle, although intersubject variation in knee angle for the preferred jumps was greater, as was to be expected. Moreover, relations between the jump height from 90° and from the preferred knee angle on the one hand, and isometric torque development on the other hand, were also very similar. Because of these similarities, the data from the preferred position did not add anything to the main findings of this study and will therefore not be presented.

Total duration of the jumping part of the measurements, including the preparation of the subject, was about 75 min. This was followed by a 15-min transfer into the dynamometer, where the remaining measurements (duration about 35 min) were done as described below.

Isometric torque development. The subjects performed three isometric knee extension MVC, which were made with strong verbal encouragement and with online visual feedback, with 4 min of rest in between. In addition, at least two maximal knee flexion MVC were made to obtain maximal surface EMG values of knee flexors. An extra attempt was made only if the last attempt of a MVC was more than 5% higher than the first.

This was followed by five attempts to increase knee extension torque from a fully relaxed state, that is, without any preceding countermovement, as fast (and hard) as possible (14). The emphasis of instruction was on "fast" (26), but peak torque had to reach at least 65% of MVC values. Attempts during which torque deviated from baseline values (signal noise was smaller than 0.1% MVC) during the 100 ms immediately preceding the onset of the maximal attempt were discarded. Onset of fast torque development (start of the contraction) was defined as the point at which the filtered (fourth-order 50-Hz low-pass) force curve exceeded average baseline force by more than three standard deviations, which typically was about 1 N measured at the shin transducer (14). Measurements were made at the 120° knee angle because this is the optimal angle for maximal torque production (14). The ability for fast initial torque development is independent of knee angle (14).

Subjects were encouraged to improve on the time it took to develop torque from 2 to 30% MVC value, which was used as feedback during the experiments. Two minutes of rest were allowed between all fast contractions.

Subsequently, five correct fast contractions from a pretension level set at 15% MVC were made. We measured fast torque development from pre-tension because it can be argued that many movements in everyday life start from pretension; using the moment that the center of body mass produces in the knee joint, it was calculated that 15% MVC is approximately equal to the knee extension torque needed to stand in squat position with 90° knee angles. The fast contractions without pre-tension were included for comparison with our recent study (14).

Data Analysis

To enable comparison between our previous (14) and present experiments on the dynamometer, TTI-40 was calculated. Note that correlations presented in the present study between jump height and TTI-40 were similar for other TTI between 10 and 80 ms. In the contractions with pre-tension, torque and EMG were corrected for baseline values. The average value during the 100 ms prior to torque and EMG onset was subtracted.

As an indication of voluntary activation at the very start of muscle contraction, rectified and normalized surface EMG signals obtained during fast voluntary contractions were averaged for the 40 ms before the onset of torque development (EMG-40). Previously, 76% of the variation in TTI-40 among subjects has been accounted for by EMG-40 (14). Although electromechanical delay in our setup is about 20 ms during electrical stimulation leading to a clear, sharp increase of torque (14), the rather long time span of 40 ms was used to include all EMG activity before the (less steep) torque increase at the beginning of the voluntary contractions (14).

In contrast to the one-legged isometric contractions in the dynamometer, during jumping, the exact start of knee extensor torque development cannot be established. The vertical GRF results from the combined action of many flexor and extensor muscles around hip, knee, and ankle joint. It is reasonable to assume that a (well timed) high activation of the leg muscles will result in a steeper rise of GRF and higher jumps compared with jumps with lower activation of the leg muscles (30). However, because of the fluctuations in GRF, the onset of GRF rise could not be established as accurately as the onset of isometric torque development in the dynamometer, particularly compared with the contractions from the fully relaxed state. For these reasons, the start of GRF rise was defined as the first moment that GRF exceeded the lowest force immediately before the rise in GRF by more than 10 N (left vertical lines in Figure 2 where GRF goes

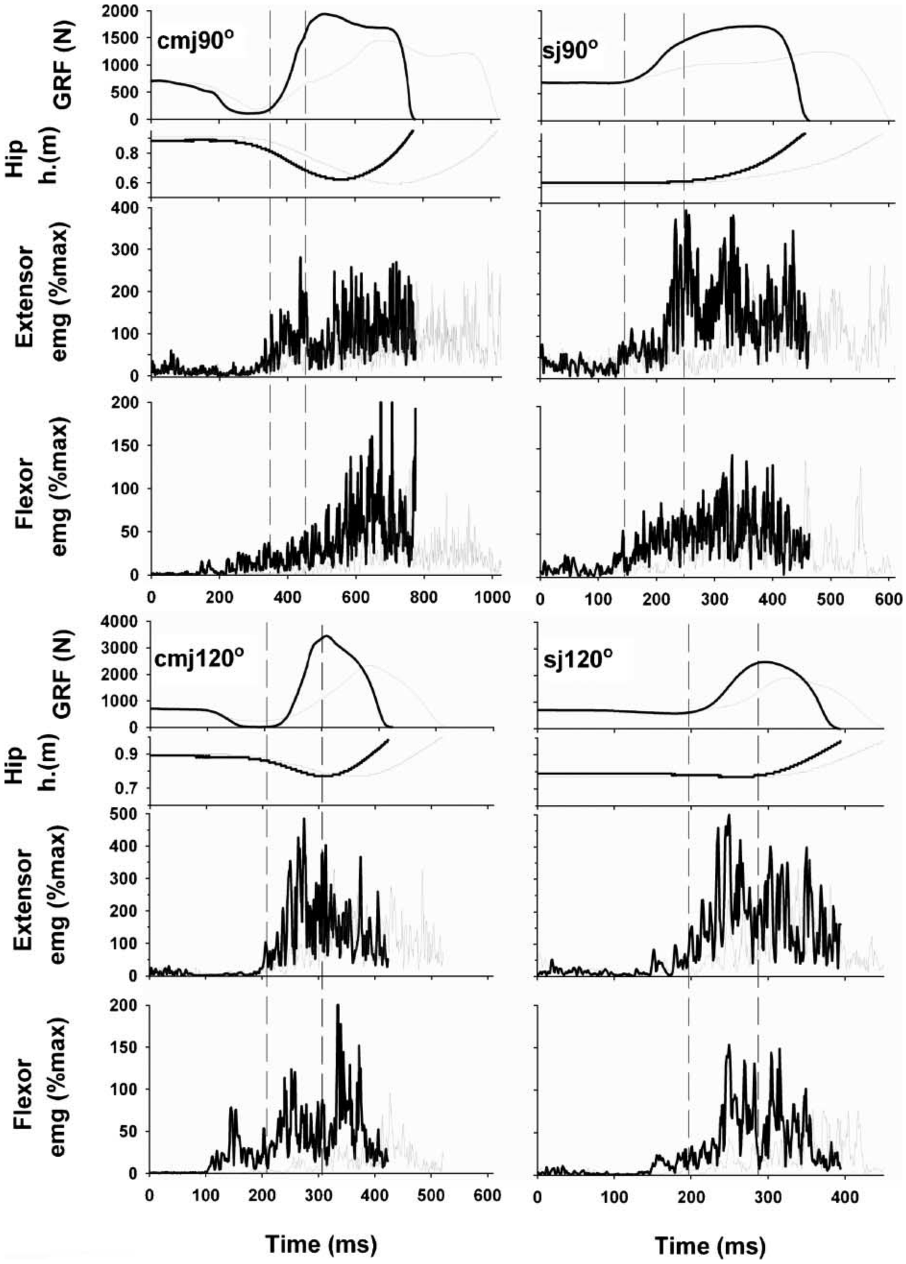

FIGURE 2—Vertical ground reaction forces (*top row in each of the four panels*), height of the hip marker (*second rows*), average extensor (*third rows*), and flexor EMG (*bottom rows*) against time (*x-axes*) for a subject with a high ability for fast torque development (subject 3, *thick traces*; see also Fig. 3) and a subject with much slower torque development (subject 9; see also Fig. 3) during CMJ (*left*) and SJ (*right*) from a 90° (*top*) and 120° (*bottom*) knee angle. The two *vertical dashed lines* in each of the four panels denote the first 100 ms of the rise in GRF. Note that for each of the jumps, there is a steeper increase in GRF, resulting in a greater FTI-100 in the faster subjects. This is accompanied by higher values for extensor and flexor EMG, resulting in shorter jump durations and higher jumps for the faster subjects (traces end at take-off). Also note that the time axis is different in each panel.

upwards). Note that the time needed by our best jumpers to reach peak GRF during SJ and CMJ starting from the 120° knee angle was about 100 ms (Fig. 2). Therefore, force time integral (FTI) after the onset of the rise in GRF was calculated for 100 ms. In addition, the delay between the EMG of the different leg muscles and the start of their contribution to the increase in GRF cannot be accurately established, particularly not during a CMJ. Therefore, EMG of the knee flexor and extensors and the FTI were all calculated for the first 100 ms of rise in GRF (EMG-100 and FTI-100) without any attempt to correct for electromechanical delay. EMG (normalized to the maximal EMG obtained at the plateau of an MVC in the dynamometer) was corrected for "baseline" activity by measuring the EMG activity well before (about 150 ms) the jump (i.e., with subjects either in a squatted position or standing upright (CMJ)) and subtracting this value from the EMG before calculation of EMG-100. The dotted vertical lines in Figure 2 denote the time span over which the GRF was integrated. The GRF a few milliseconds before the left vertical line (start of the positive rise) was subtracted from the GRF signals before FTI-100 was calculated. It is important to note that EMG-100 and FTI-100 were merely used to obtain indications about voluntary activation and rate of force development during jumping, without any attempt to directly link the two together. Direct linking of both parameters seemed appropriate only for the dynamometer measurements. Note that during the 100-ms time window that we analyzed (between the dotted vertical lines in Fig. 2), the hips moved downward during a CMJ, whereas during SJ, this 100 ms was approximately the time before any noticeable rise of the hips occurred (Fig. 2). The EMG signals of subject 2 (Table 1) obtained during jumping could not be used in the data analysis because of technical problems that had occurred with the synchronization of these EMG signals with signals from the force plate and cameras.

Similar to our previous study (14), variation in EMG-40 in the dynamometer and EMG-100 (during jumping) among the three different knee extensor and the two flexor muscles was seen between different attempts, but no significant differences were found among the three extensors or between the flexor muscles. Therefore, after normalization to values obtained during MVC and rectification of the signals for each muscle, the average values of the extensor and flexor muscles were calculated to determine voluntary extensor and flexor muscle activation, respectively.

Statistics

The results are presented as mean values ± SD. Effect of jump type was tested for significance ($P < 0.05$) with repeated-measures ANOVA followed by Bonferroni *post hoc* tests.

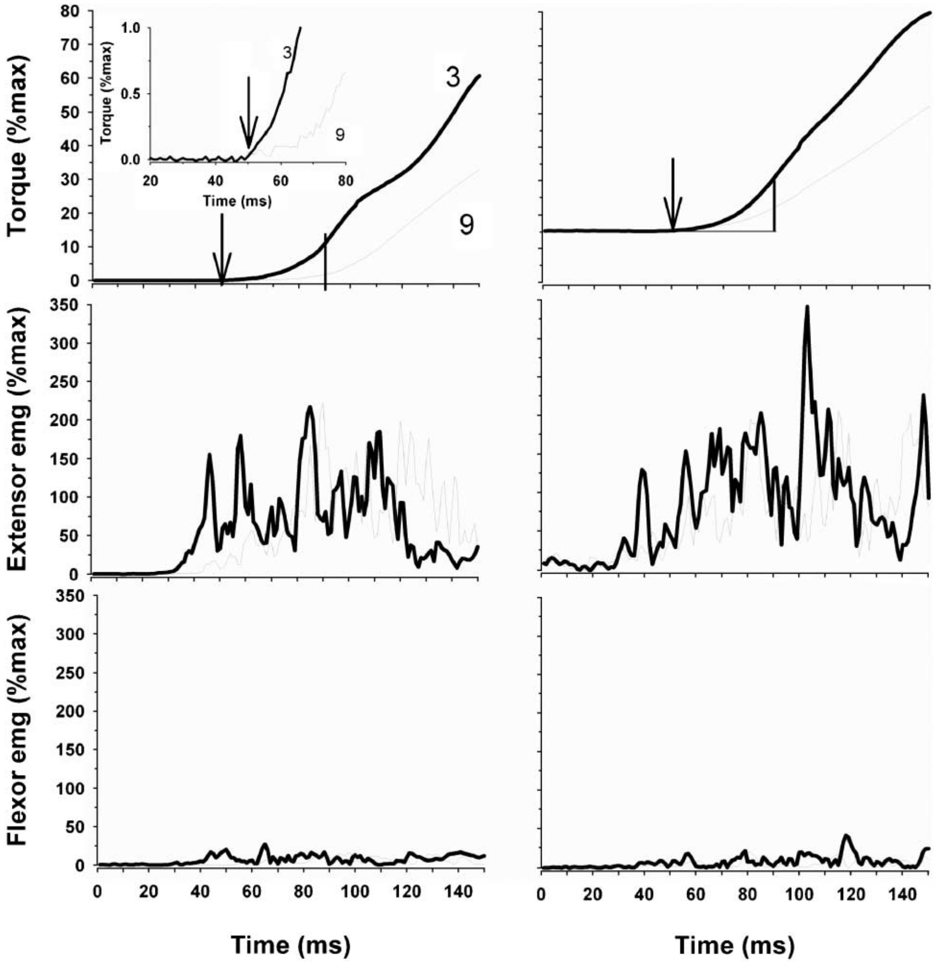

FIGURE 3—Torque time traces (*top*) and average extensor (*middle*) and flexor muscle EMG (*bottom*) of two subjects during fast maximal one-legged isometric knee extension at a 120° knee angle without (*left*) and with (*right*) pre-tension. Subject 3 (*bold traces*) and subject 9 (*thin traces*), respectively, had a high and low ability for fast torque development but had otherwise very similar characteristics (Table 1). Torque onset is indicated by the *arrows* in the *top panels*, in which the *vertical lines* denote the first 40 ms of torque development—the time over which torque time integral was calculated. Note the high peaks in average extensor EMG at the start of the contractions in subject 3 compared with subject 9, who displays a far more gradual increase of EMG. Average flexor EMG is low for both subjects. The magnification in the *top left panel* shows more clearly that torque indeed started to rise at t = 50 ms in both subjects.

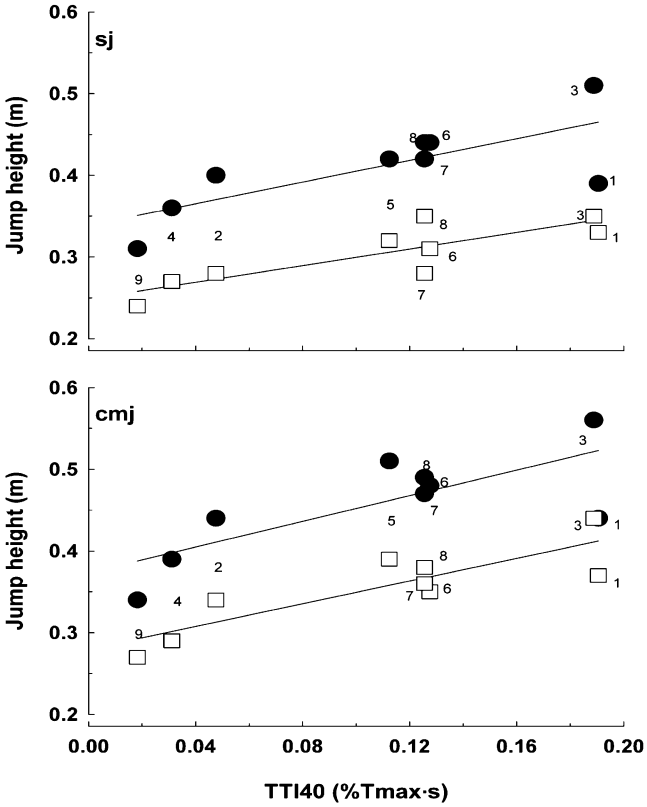

FIGURE 4—Jump height of the subjects as function of torque time integral over the first 40 ms of one-legged isometric knee extension (*x axis*) for the SJ (*top*) and CMJ (*bottom*) from a 90° (*black circles*) and 120° (*white squares*) knee angle. *Numbers* indicate the different subjects (see Table 1). There were significant ($P < 0.05$) positive linear relations between both parameters in each of the four jumps.

Pearsons's correlation coefficient was calculated to establish significance of correlation.

RESULTS

Maximal isometric knee extensor torque (Tmax) was 285 ± 43 N·m and ranged from 221 to 318 N·m. Superimposed electrical stimulation upon MVC showed that at the plateau of the isometric contraction, voluntary muscle activation was high in all subjects (95 ± 5%) and not significantly different from 100%. As expected, TTI-40 (normalized to Tmax and corrected for pre-tension torque) was significantly higher for fast isometric contractions starting with pre-tension (0.15 ± 0.06% Tmax per second) than for contractions starting without pre-tension (0.11 ± 0.06% Tmax per second).

Figure 3 shows a typical example of torque and EMG of a "fast" (subject 3) and a "slow" subject (subject 9) at the beginning of a fast isometric knee extension. At first sight, it may appear as if the start of torque development (indicated by the arrow) in the left top panel is not correctly assessed for subject 9. However, this is an optical illusion caused by the scaling (80%) of the vertical axis. On closer inspection, using a far more sensitive scaling of 1% on the vertical axis (see the inset at the top left panel), it becomes clear that both subjects indeed start to develop torque at t = 50 ms, but that subject 9 does it at a relatively slow rate. These two subjects in particular were selected as typical examples in this figure and in Figure 2 because of their very similar age, height, body weight, Tmax, and sport activity (Table 1). Note the steeper rise of torque after the start of the contraction in subject 3, which is accompanied by much higher early peaks in the EMG of the knee extensors compared with subject 9. Indeed, there was a ninefold range among the subjects in their ability for fast torque development: TTI-40 without pre-tension ranged from 0.02 to 0.19% Tmax per second (Fig. 4), with a similar range in EMG-40. Moreover, there were significant positive linear relations ($P < 0.05$) between normalized EMG-40 and normalized TTI-40 in contractions without (r = 0.81) and with (r = 0.80) pre-tension. Furthermore, comparing the contractions with and without pre-tension revealed that there were significant positive linear relations for TTI-40 (r = 0.95) and EMG-40 (r = 0.79) between both types of isometric torque development.

SJ and CMJ height (m) from 90 and 120° knee angle were 0.41 ± 0.06 (SJ 90: range 0.31–0.51), 0.46 ± 0.06 (CMJ 90), 0.30 ± 0.04 (SJ 120), and 0.36 ± 0.05 (CMJ 120). Jumps from the 90° knee angle were significantly higher than jumps from the 120° angle, and jumps preceded by a countermovement were significantly higher than when started from a squatting position ($P < 0.05$).

In Figure 2, vertical GRF, height of the hip marker, and average knee extensor and flexor EMG during the four different jumps are plotted against time for a good jumper (subject 3 (thick lines), SJ 90 = 0.51 m) and a poor jumper (subject 9 (thin lines), SJ 90 = 0.31 m), which are the same subjects as in Figure 3. Average jump height of subject 9 across the four jumps was 62.8 ± 3.5% of that of subject 3. The traces of the two subjects are aligned at the start of the rise in GRF (leftmost vertical dashed line in each panel). The traces stop at take-off (GRF = 0). Note that the time interval between the first and second vertical dashed line in Figure 2 is 100 ms, which was approximately the duration of the steep part of the rise in GRF for the better jumpers. Figure 2 illustrates that good jumpers, like subject 3, had a steeper rise in GRF, resulting in higher values for the FTI over the first 100 ms (FTI-100), and made a faster countermovement at the beginning of a jump, in which they often completely unloaded the force platform (GRF becomes zero) and had a shorter jump duration compared with the poor jumpers such as subject 9. Note that the

TABLE 2. Relation between EMG and force time integral (FTI) and jump height.

	FTI-100		Extensor EMG-100		Flexor EMG-100	
Jump Height	r	*P*	r	*P*	r	*P*
SJ 90	0.74*	0.02	0.75*	0.03	0.67	0.07
CMJ 90	0.49	0.19	0.71*	0.04	0.79*	0.02
SJ 120	0.59	0.09	0.61	0.10	0.58	0.13
CMJ 120	0.86*	0.003	0.82*	0.01	0.80*	0.02

FTI-100, force time integral calculated for the first 100 ms of rise in ground reaction forces; EMG-100, EMG calculated for the first 100 ms of rise in ground reaction forces; SJ 90, squat jump starting from 90° knee angle; CMJ 90, countermovement jump starting from 90° knee angle; SJ 120, squat jump starting from 120° knee angle; CMJ 120, countermovement jump starting from 120° knee angle.
* $P < 0.05$.

TABLE 3. Relation between isometric torque parameters and jump height.

	TTI-40		TTI-40 pre-Tension		Tmax	
Jump Height	r	*P*	r	*P*	r	*P*
SJ 90	0.75*	0.02	0.67*	0.04	0.003	0.99
CMJ 90	0.76*	0.02	0.71*	0.03	−0.08	0.83
SJ 120	0.84*	0.004	0.72*	0.03	0.02	0.95
CMJ 120	0.86*	0.003	0.79*	0.01	−0.16	0.68

TTI-40, torque time integral for the first 40 ms after torque onset; SJ 90, squat jump starting from 90° knee angle; CMJ 90, countermovement jump starting from 90° knee angle; SJ 120, squat jump starting from 120° knee angle; CMJ 120, countermovement jump starting from 120° knee angle.

* $P < 0.05$.

better jumper (subject 3) did not have a steeper increase of GRF because he was stronger than subject 9 (actually, subject 9 was a bit stronger; see Table 1), but that similar to the situation in the dynamometer, subject 3 had a higher rate of force development (greater FTI-100), which resulted in a higher peak GRF during the jump. In addition, the better jumpers had higher average EMG values, not only for the knee extensors, but also for the knee flexors. Indeed, and especially during CMJ 120, there were significant positive linear relations between jump height, FTI-100 of the GRF, and EMG-100 of the knee flexor and extensor muscles (Table 2). The correlation coefficients were lower for SJ 90 and CM J90 and not significant for SJ 120 (Table 2).

In accordance with our first hypothesis, there were significant positive linear relations between normalized TTI-40 (with and without pre-tension) and jump height (Fig. 4) but clearly not between Tmax and jump height (Table 3). TTI-40 without pre-tension showed somewhat higher correlations with jump height than TTI-40 with pre-tension (Table 3). Thus, if anything, TTI-40 without pre-tension has a higher predictive value for jump height than TTI-40 obtained with pre-tension. In addition, subjects found it more difficult to develop torque rapidly without countermovement from a steady pre-tension level than from full relaxation. Moreover, the determination of the start of torque rise is less accurate from a fluctuating baseline around 15% MTC than from a flat line during complete relaxation. For these reasons, we focused on the relations between jump height and TTI-40 obtained from contractions without pre-tension. When we expressed jump capacity in terms of the increase of potential energy of the subjects during the jump (m·g·h), the relations between TTI-40 and jump performance were somewhat higher than those reported in Table 3, with correlation coefficients of 0.91 (SJ 90), 0.88 (SJ 120), 0.91 (CMJ 90) and 0.95 (CMJ 120).

There was no clear indication for the relations between TTI-40 and jump height to be stronger for jumps starting from the 120° knee angle compared with the 90° knee angle (second hypothesis). Note that despite the high correlations between TTI-40 and jump height and the good correlations between TTI-40 and EMG-40, the correlations between EMG-40 and jump height were weak and mostly not significant: SJ 90 (r = 0.59, $P = 0.09$), SJ 120 (r = 0.64, $P = 0.06$), CM J90 (r = 0.59, $P = 0.10$), and CMJ 120 (r = 0.73, $P = 0.03$).

DISCUSSION

The main finding of the present study is the high positive linear relations between the first 40 ms of fast voluntary one-legged knee extension torque development (TTI-40) and two-legged jump performance in a group of healthy, active young males, thereby confirming our first hypothesis. However, the relations between TTI-40 and jump height were strong in all conditions, and we could not confirm our second hypothesis; there was no clear indication that relations between TTI-40 and jump capacity were better for jumps with a shorter push-off phase (starting from a 120° knee angle) and, therefore, less time for force development than jumps starting from a 90° knee angle.

Although various measures to quantify the rate of isometric torque development have been used to investigate the possible relationship between that rate and jump performance, in general, correlation coefficients between such parameters and jump height were found to be low (24,31) or not significant (6,15,22). Paasuke et al. (24) reported significant correlations (0.62–0.83) between the absolute maximal rate of unilateral isometric torque development (MRTD) and jump height in trained and untrained subjects. However, measures of isometric contractile speed should be normalized to the maximal torque produced. The fact that this has not always been done may account for some of the conflicting findings in the literature. Unfortunately, Paasuke et al. (24) did not report the relation between jump height and normalized MRTD.

In the present study, the intersubject variation in Tmax was limited (Table 1), and there was not even a trend for a relation between MVC and jump height. MVC torque has been found to be unrelated (5,20) or only moderately related (16) to jump height. Hakkinen et al. (17) reported a higher correlation (0.81), but this was in a heterogeneous group that included female and male subjects. Thus, in a homogenous group of subjects, differences in maximal torque do not seem to account for much of the variation in jump height (31). The present study confirms and strengthens this conclusion because we established, using superimposed electrical stimulation, that voluntary activation during MVC was nearly maximal in all subjects.

To the best of our knowledge, the present study is the first to relate the very early phase of single-joint isometric torque development to a more natural, power-demanding multijoint type of movement. Recently, it has been argued that the TTI of the early phase of torque development would perhaps be the most important parameter for the execution of fast ballistic and/or power-demanding tasks (2). The present study supports this argument, at least for the knee extensors in relation to jump performance. The significant relations between TTI-40 and jump height found in the present study may seem surprising. Both tasks are very different, and it has been suggested that isometric contractions (6,23,28,31) and/or contractions performed in an open kinetic chain (8), such as in the present study, would not be movement-specific enough to be able to predict performance during a more (complex) natural movement such as a jump. In the present study, we took a different point of view, which was based on our recent finding that there was a ninefold range in TTI-40 during isometric knee extension among normal healthy subjects (which we confirmed in the present study) (14). Moreover, 76% of the variation in TTI-40 was accounted for by the subjects' ability to produce high peak values in the surface EMG of the knee extensors during a 40-ms period before the start of torque development (14). In both the present and in our previous study (14), the subjects differed widely in their ability for this burstlike muscle activation, whereas their capacity for maximal activation at the plateau of a MVC was similarly high. Of the present subjects only subject 7 did some (occasional) strength training, but as in our previous study (14), none of the subjects were specifically trained for one-legged fast isometric contractions. Therefore, we hypothesized that the ability for fast muscle activation of the knee extensor muscles would be more subject- than task dependent, as long as the task at hand could be performed by all subjects and was not a complex new task. In addition, model studies confirm that a fast onset of activation of the leg muscles is beneficial for jump performance because a high-active state at the beginning of a jump will enhance the work produced by the muscles and, consequently, improve jump height (9), provided that coordination of activation among the different leg muscles stays optimal (10,30). Our subjects were healthy, active subjects, and although they were not specifically trained, they essentially were skilled jumpers. We confirmed our hypothesis that subjects who were fast during isolated single-joint isometric muscle contractions in the dynamometer (high TTI-40) would also be fast during a complex multijoint movement (high FTI-100) and, consequently, would perform well during jumping, and vice versa. Given the number of subjects studied, the present findings do not allow us to conclude that there were better correlations between TTI-40 and jump height when jumps started from the 120° knee angle compared with the 90° knee angle, which was our second hypothesis. Possibly, the same neuromuscular factors (including a fast contraction onset and, possibly, fiber-type composition) that determine jump performance from the 120° knee angle already dominate performance in jumps from the 90° angle.

The correlation coefficients for the relation between TTI-40 and EMG-40 (0.81 and 0.80) are within the range found in a recent study in which the final relation between both parameters ($r = 0.87$) was based on the average values for TTI-40 and EMG-40 obtained in four measurements ($0.76 < r < 0.91$) made at different knee angles and days (14). Given the variation in the EMG-40 we observed between trials (14), in future experiments it may be better to let the subjects make more attempts and then take the average values of the best three or four trials. Nevertheless, in healthy young males, the ability for fast neural activation seems to be the dominating factor in explaining the intersubject variation in TTI-40 (14) and the present results. However, the present results also show that there were only weak (mostly not significant) linear relations between EMG-40 obtained in the ergometer and jump height. Moreover, when both TTI-40 and EMG-40 were added into a linear regression model with jump height (CMJ 120) as the dependent variable, EMG-40 did not significantly increase the proportion of explained variance in jump height that was already obtained with TTI-40 as the input parameter. These findings clearly suggest that intrinsic muscle factors such as fiber-type composition of the muscles (1,11) and tendon stiffness (25) also contributed to the intersubject variation in TTI-40 (4) and jump height. However, high-level athletes of (inter)national caliber and athletes who were highly trained for endurance (e.g., long-distance runners) or power events (sprinters or weight lifters) were excluded from participation in the present study to minimize the potential effects of differences in muscle fiber-type composition and specific training. Moreover, in our recent study using a similar subject group, there was not much variation in TTI-40 obtained with maximal femoral nerve stimulation, suggesting that the between-subject variation in fiber-type composition was limited and that neural activation dominated voluntary fast torque development (14). Nevertheless, in the present study, we cannot exclude that muscle contractile properties contributed to the variation in TTI-40 and jump height and/or that the capacity for fast neural activation and the percentage of fast muscle fibers of the knee extensors covaried among our subjects.

Although during jumping the changes in GRF cannot be accurately related to EMG of the different leg muscles involved, there were strong indications that the ability for fast voluntary muscle activation also accounted for much of the difference in performance among subjects during jumping. For instance, during CMJ 120 there were high correlations ($0.80 < r < 0.86$) between jump height on the one hand and, on the other hand, FTI-100 and EMG-100 of the knee extensor as well as the knee flexor muscles. The latter finding suggests that the ability for fast neural activation was not restricted to the knee extensor muscles but was similar for other leg muscles in the same subject. This is speculative because we did not measure TTI-40 of other muscles groups. However, the correlations between TTI-40 of the knee extensor muscles and jump performance are rather high considering that we only measured one muscle group, whereas during jumping, other muscles such as the gluteus maximus and the hamstrings produce more than half the work (9) and, consequently, make important contributions to the height of the jump. Therefore, it seems plausible that within a subject, the onset of voluntary activation will be relatively fast (or slow) in all leg muscles involved during a jump, which, in addition, could be beneficial for the execution of a well-coordinated movement.

Although none of our subjects were specifically trained for either of the two tasks, the higher EMG bursts at the start of a contraction in our faster subjects probably reflect a higher motoneuron excitability and/or stronger central drive. Motoneuron excitability and/or the drive in descending pathways from upper motor centers may increase after resistance training (3). Others have found concomitant increases of surface EMG (18) and single-motor-unit EMG (29) and rate of torque development after a period of training. In the present study, only subject 7 performed some power-type training, but he was an average performer, and the other subjects were not and had not been involved in strength/power training. Therefore, the current results cannot straightforwardly be explained by a different training status among our subjects.

Thus, to a large extent, torque increase during the first 40 ms of fast one-legged isometric knee extensor torque development (TTI-40) explained the variation in two-legged jump height. Subjects who were fast during an isolated unilateral single-joint muscle contraction were also fast and performed well during a complex bilateral multijoint movement, and vice versa. Moreover, the intersubject variation in TTI-40 and jump performance seems to be accounted for mainly by difference in ability among subjects to produce a high initial efferent neural drive immediately before the onset of movement.

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