

Isometric Knee-Extensor Torque Development and Jump Height in Volleyball Players

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ABSTRACT

DE RUITER, C. J., G. VERMEULEN, H. M. TOUSSAINT, and A. DE HAAN. Isometric Knee-Extensor Torque Development and Jump Height in Volleyball Players. *Med. Sci. Sports Exerc.*, Vol. 39, No. 8, pp. 1336–1346, 2007. **Purpose:** The goal of the present study was to determine the contribution of the intrinsic muscle properties and muscle activation of the knee extensors to the maximal rate of unilateral isometric torque development and to relate both factors to maximal bilateral jumping performance in experienced jumpers. On the basis of previous studies, we hypothesized that maximal rate of torque development during maximal effort isometric contractions and jump height would depend on the subjects' ability for maximal muscle activation rather than on the muscle's contractile properties. **Methods:** Eleven male elite volleyball players (20 ± 2 yr, means \pm SD) performed squat jumps starting from a 120° knee angle (SJ120; full extension = 180°) and countermovement jumps. In addition, maximal voluntary and electrically evoked unilateral isometric knee-extension torque development (120° angle) was obtained. Torque time integral for the first 40 ms after torque onset (TTI40) and (time to) maximal rate of torque development (MRTD) were calculated. Muscle activation was quantified using surface EMG. **Results:** Voluntary TTI40 was significantly related to the preceding EMG ($r^2 = 0.83$) and negatively related to the time to MRTD ($r^2 = 0.64$). Voluntary MRTD and TTI40 were not related to their respective values obtained during electrical stimulation ($r^2 < 0.04$). Only electrically evoked MRTD was significantly related to jump height (e.g., $r^2 = 0.70$ for SJ120). **Conclusions:** As expected initial maximal voluntary isometric torque development correlated with muscle activation and not with muscle contractile speed. However, unexpectedly, only the latter could predict jump performance in skilled jumpers. **Key Words:** HUMAN, ELECTRICAL STIMULATION, EMG, MUSCLE ACTIVATION

It seems generally accepted that jump performance is a good measure of leg-extension power. Because muscle power is the product of contractile velocity and force, it is not surprising that researchers have hypothesized that jump performance would be positively related to either maximal knee-extension torque and/or some measure of contractile speed. However, in light of the logical basis of

these hypotheses, the results of such studies have in general been rather disappointing. Jump height has been found to be related to maximal isometric knee-extension torque but only in a very heterogeneous subject group (15); others have failed to find any significant relationships between both parameters (3,18,30). In addition, relationships between measures of muscle speed obtained during voluntary contractions and jump performance were found to be poor (20,22,28) or absent (4,13,20,21).

In principle the rate of isometric torque development *in vivo* depends on the properties of the muscle tendon complex and on muscle activation. We are unaware of studies in which the relative importance of both factors on torque development was investigated. Moreover, the relative contribution of muscle properties and muscle activation to torque development may be task dependent. Therefore, it is perhaps not surprising that usually nonsignificant (4,13,21) or poor relationships (22,29) between the rate of

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voluntary isometric torque development assessed in a dynamometer and jump height have been found. In this context, it has been argued that specificity of one-legged isometric contractions is not high enough to be able to predict performance during a more complex whole-body movement such as two-legged jumping (4,26).

Aagaard et al. (1) focus on the initial phase of isometric torque development and found that power training resulted in improvements of the torque time integral for the first 40 ms of isometric knee extension. De Ruiter et al. (11) have compared the torque time integral of the first 40 ms (TTI40) of maximal voluntary contractions with the TTI40 during maximal electrical nerve stimulation. Electrically evoked TTI40 allowed establishing maximal isometric contractile speed of the knee-extensor muscles, whereas the ratio of voluntary TTI40 and electrically evoked TTI40 showed the extent to which the subjects were able to make use of their muscles' maximal potential for isometric torque development during maximal voluntary contractions. They have shown that this ratio varied considerably among subjects (0.1–0.8) and that 75% of the variation among subjects could be explained by differences in the ability of subjects to generate high EMG peaks at the initiation of the contraction (11). In a recent study, de Ruiter et al. (12) have further found that torque increase during the first 40 ms of a maximal voluntary isometric knee extension was positively related ($0.75 < r < 0.86$) to squat and countermovement jumps. However, in this last study the muscles' maximal potential for torque development was not assessed with electrical stimulation, hence information about the muscle properties was lacking. This may be important because jump performance has been shown to correlate with fiber type composition (7) and tendon stiffness (6), which are also expected to be important determinants of torque development in a dynamometer (23,25). Therefore, part of the high correlation between maximal voluntary isometric torque development and jump height in our previous study (12) may have been caused by intersubject differences in the intrinsic contractile speed of their muscles. The subject groups in our previous studies (11,12) were reasonably homogeneous with respect to training status, athletes

specifically trained for either endurance or power sports were excluded. Nevertheless, it is possible that the subjects differed in training history and/or jumping skills, which could affect the interrelations between muscle activation, muscle properties, and jump height. Therefore, to further enhance group homogeneity with respect to training status and jumping experience, the present investigations were performed in well-trained jumpers (members of the Dutch national talent volleyball team).

We firstly aimed to determine the contribution of properties of the muscle tendon complex and of muscle activation on voluntary isometric torque development of the knee extensors. The second aim was to relate both factors obtained in the dynamometer to the more complex task of jumping. On the basis of our recent findings (11,12), we hypothesized that among elite volleyball players the capacity for maximal muscle activation would determine the speed of voluntary isometric torque development and jump performance, whereas intrinsic contractile speed of the knee extensors was expected to be of lesser importance during maximal voluntary isometric torque development as well as jumping.

METHODS

Subjects

The local ethics committee approved the study. Eleven healthy male elite volleyball players (Table 1) signed informed consent and came to our lab twice with at least 1 d in between. Subjects were measured at the same time of day on both occasions. The subjects were members of a team, which has been created to enhance the development of the most talented young male volleyball players in the Netherlands. This team plays in the highest national division and became third in the playoffs later on during the season. The players were tested in midseason (February). They trained every day for 3–4 h, with a large emphasis on physical aspects. For example, they were involved in weight lifting exercises two to four times a week during the entire season. They did not perform any weight lifting exercise during the

TABLE 1. Subject characteristics and maximal isometric torque production.

Subject	Age (yr)	Body Mass (kg)	Height (cm)	% Fat	Maximal Voluntary Contraction Extension (N·m)	Maximal Voluntary Contraction Flexion (N·m)	Voluntary Activation (%)	Maximal Torque Capacity Extension (N·m)
1	18	71.0	196	14.0	229	115	79	291
2	24	87.5	196	11.0	439	153	94	465
3	21	87.0	201	14.0	289	125	69	418
4	18	80.5	200	12.0	371	114	91	409
5	23	82.0	190	14.0	355	153	86	414
6	20	90.0	200	10.5	294	129	83	353
7	19	86.0	205	9.5	408	173	92	445
8	19	82.0	190	14.0	286	141	74	387
9	20	89.0	208	12.5	252	137	73	344
10	20	93.0	200	11.5	462	175	94	489
11	20	86.0	200	10.0	399	124	99	403
Mean	20	85	199	12	344	140	85	402
SD	2	6	5	2	75	20	10	54

36 h before they came to our laboratory, but otherwise they continued to train according to their regular program as much as possible.

Torque Measurement

In principle, the contractile properties of the knee extensors of the right leg were investigated using a custom-made dynamometer. However, in three subjects the left leg was investigated because they experienced some pain in their right knee during forceful muscle contractions. All subjects indicated that they would kick a ball with the right leg. 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/200 Hz, Bienfait B.V. Haarlem, The Netherlands) placed 29 cm distally from the knee joint, which measured the force exerted at the shin (see Fig. 1 in de Ruiter et al. (12)). The real-time force, corrected for gravity, applied to the force transducer was displayed on line on a computer monitor and digitally stored (2 kHz). Measurements were done at the 120° knee angle set manually using a goniometer and using as reference landmarks the greater trochanter, the lateral epicondyle, and the lateral malleolus, with subjects exerting a force of about 50% MVC. For more details about this procedure, see de Ruiter et al. (11).

To ensure high stiffness between shin and aluminum 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. In previous experiments, changes in position of the dynamometer arm were measured during voluntary

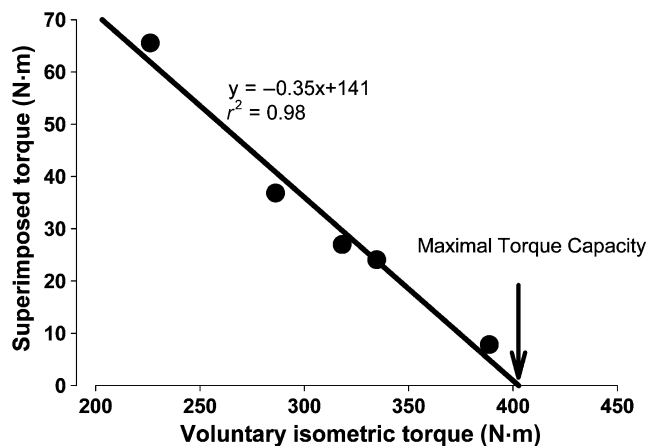


FIGURE 1—Typical example of the extra torque in response to electrical stimulation (three pulses at 300 Hz) superimposed during voluntary isometric contractions as a function of the voluntary contraction level (x -axis) in one of the subjects. Note that the point where the regression line fitted through the data points ($r^2 = 0.98$) crosses the x -axis (just over 400 N·m) denotes the maximal torque capacity (MTC) of this subject's knee-extensor muscles.

knee extensions using a Plunger dial indicator (Linear Tools Ltd. Isleworth, UK) mounted on an external frame and placed against the dynamometer arm. The measured stiffness was 7143 N·m per degree. Despite our measures to make the setup as stiff as possible, an unavoidable $3\text{--}7^\circ$ increase in knee angles, attributable to soft-tissue compression, always occurs when the knee-extensor torque increased from zero to maximal values (11).

Electrical Stimulation and Maximal Isometric Torque

Constant current electrical stimulation (100- μ s 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). After 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 200 and 400 mA, and it was assumed that at that point all of the knee-extensor muscle fibers were fully activated. The maximal rate of torque development (MRTD and TTI40) of the knee extensors was determined by applying a burst of eight pulses at 300 Hz (octet) on the relaxed muscle (11).

During voluntary isometric contractions (duration of 4–5 s with 4 min of rest in between) of increasing intensity starting at about 75% of maximal effort, triplet stimulation was applied by the investigator when torque reached a plateau. The torque enhancement from this superimposed triplet was used to show the subjects that their knee extensors were able to generate more force than they voluntarily were able to generate. In this manner it served as positive feedback, to encourage the subject to improve themselves in the next attempt, with a total of five or six attempts. More importantly, however, when the superimposed torque is plotted as a function of MVC torque, the data points can be fitted using linear regression. Such a plot shows that for high torques there is a linear decline of the superimposed torque as a function of MVC torque (Fig. 1). If a subject is able to fully recruit and maximally activate all his muscles fibers during a MVC the superimposed torque is zero. However, most subjects are unable to accomplish this. In these subjects, the linear regression can be extrapolated to the point where superimposed torque would be zero (Fig. 1). In all subjects, the point where the regression lines intersects the x -axis was defined the maximal torque capacity (MTC) of the muscle (Fig. 1). In the present study MTC was calculated for every subject (at both days) to determine the maximal isometric strength of each subjects' knee-extensor muscles. At each day voluntary activation (VA) was subsequently defined as the ratio of the highest MVC over MTC times 100%. It is very

important to have an accurate measure of MTC, because the absolute rate of isometric torque development depends on maximal isometric torque. The most direct way to assess MTC would be 500–1000 ms of maximal tetanic nerve stimulation (150 Hz); however, this is very stressful (personal experience), unpleasant, and may even be harmful. Therefore tetanic nerve stimulation is not an option to assess MTC of the knee extensors.

Surface Electromyography

Electromyographic activity of the vastus lateralis, vastus medialis, rectus femoris, and long head of the biceps femoris muscle was recorded using Ag/AgCl surface electrodes (11.5 mm, Blue Sensor N, Ambu A/S, Ballerup, Denmark). After shaving, roughening, and cleaning the skin with 70% ethanol, electrodes were placed in a bipolar configuration with an interelectrode distance of 20 mm at the distal third of the muscles. For the biceps femoris, electrodes were placed parallel to the long axes of the muscle belly. For the knee extensors, electrodes were placed in line with the approximate muscle fiber direction. Fiber orientation during contractions was established in pilot experiments on another subject group using a 7.5-MHz linear ultrasound probe (Aloka SSD 5000 Prosound). For rectus femoris, both electrodes were placed at the lateral side of the central tendon. Reference electrodes were placed on the left and right patella and tibia. Surface EMG signals were amplified ($\times 1000$), digitized (2 kHz), and stored with the force signal on computer disc. The custom-built amplifiers (INPHO Sense Medical Electronics, Kortenhoeft, the Netherlands) had a frequency response of 10 Hz (6 dB) to 10,000 Hz (12 dB), with an isolation rejection ratio exceeding 156 dB. Electrode sites were marked with a waterproof felt-tip pen to ensure identical placement of electrodes during the next session. Because all 11 players had to be tested in 4 d, and total test duration (including the jumps) already was 2.5 h for each player, we did not measure EMG during the jumps.

Jump Height

Jump height was determined using a 3D camera system (Optotrak, type 3020, Northern Digital inc., Waterloo, ON, Canada) sampling at 200 Hz. An Optotrak marker was placed on the greater trochanter of the right femur. The position data were filtered bidirectionally using a fourth-order low-pass Butterworth filter with a cutoff frequency of 8 Hz. 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 (12).

Percent Body Fat

Percent body fat was estimated using the sum of four skinfolds (triceps, biceps, subscapular, and suprailiac), which were measured three times using a Harpenden

skinfold caliper (John Bull; British Indicators Ltd., West Sussex, England). The average values of three measurements were summed and used to estimate body density (14), which was subsequently converted to percent body fat (24).

Experimental Protocol

The Optotrak marker on the hip was placed at the beginning of the experiment. The sequence of events was as follows. First, subjects performed the jumps. This was followed by anthropometric measurements and a 15-min break. Thereafter, they went to another laboratory room for the dynamometer experiments. The latter took about 90 min in total (including skin preparation and application of the electrodes). Each player was at our university for a total of 2.5 h. The subjects were instructed to come to our laboratory in a fed state (they eat their usual breakfast or lunch). In addition, during the time of the experiments they were allowed to drink and have a light snack. In the following sections, the experimental protocol will be described in more detail.

Jump Protocol

The squat jumps from the 120° knee angles (SJ120) were performed with both hands gripped together behind the back and with the trunk as straight as possible. As a warm-up, subjects performed about 12 squat jumps with increasing intensity, including some jumps from a deeper position. These warm up jumps also served to practice the start from the 120° knee angle without countermovement (similar to the maximal isometric contractions performed in the dynamometer). SJ120 were tested first on each day because these jumps are the most difficult to perform. About half the subjects had difficulties making a squat jump from the 120° knee angle without any countermovement at all, therefore jumps with a countermovement < 1 cm were included in the analysis (12). The SJ were followed by countermovement jumps without arm support and with arm support. Countermovement jumps with arm support were included at the request of the coach, to quantify the increase in jump height attributable to arm support. The reason for including the countermovement jumps without arm support was that although the execution of a SJ can be better standardized among subjects, a countermovement jump may be regarded as a more natural way of jumping. During countermovement jumps, there were no restrictions in terms of body position and knee angle, which allowed subjects to jump more freely and potentially more maximally.

The three sets of jumps were performed in this same order in all subjects on both days. Rest between consecutive jumps in a set was 1 min, and between the sets there were 3 min of rest. In each of the three sets, four or five jumps were made. If the last jump was higher than the highest jump by more than 1 cm, an additional jump was made. Squat jumps during which the hip marker lowered by more than

1 cm at the start of the jump (signifying a countermovement) were discarded.

Starting position during SJ120 was standardized as follows. Subjects were positioned in a 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, with their upper body as upright as possible/comfortable and with their hands gripped on their back. There were marks on the floor and subjects stood at exactly 1 m from a wall with their left side towards it. In front of them there was a monitor on which they saw real time video of their own body position (sagittal plane). Subsequently, parallel laser beams were aimed from exactly 4-m distance to markers (1 cm²) on the right ankle, knee, hip, and neck, while the subject maintained the correct body position and 120° knee angle. Subsequently, each time the subject had to perform a SJ120, he looked at the screen and aligned his body markers with the laser beams. After the right starting position was obtained (usually within 3 s), a verbal “go” was given by one of the investigators and the subject jumped as high as possible.

At the end of the first session, for each subject the spots where the laser beams were displayed on the wall when the subject stepped aside were marked on the wall. This resulted in a set of marks on the wall for each subject, which was used to aim the laser beams during the second session. During the second session, the laser beams were aimed at the individual set of marks on the wall, after which the subject again stood exactly 1 m from the wall. Similar to the first session, he aligned the markers on his body with the laser beams before jumping. Consequently, body position at the start of the SJ120 was very similar in both sessions.

Dynamometer Protocol

As indicated before the subjects performed five to six isometric knee extensions of increasing intensity starting at 75% maximal effort, with superimposed triplet stimulation. There was online visual feedback and there were 4 min of rest between contractions. The last three of these contractions were MVC and those were made under strong verbal encouragement. Subsequently, MTC was calculated using linear regression (see “Electrical Stimulation and Maximal Isometric Torque”). In addition, in resting periods between extension MVC, three knee-flexion MVC were made to obtain maximal surface EMG values of knee flexors. Measurements were made at the 120° knee angle because this is the optimal angle for maximal torque production (11). Moreover, the ability for maximal initial torque development is independent of knee angle (11). In addition, the squat jumps also started from this knee angle.

The MVC were followed by application of two short electrical bursts of eight pulses applied at 300 Hz (octet stimulation) on a fully relaxed muscle, with 2 min of rest in between. These octet stimulations were applied to deter-

mine the muscles’ maximal capacity for isometric torque development during full maximal activation (11).

Subsequently, five voluntary attempts were made to increase knee-extension torque from a fully relaxed state and without any preceding countermovement, as fast (and hard) as possible (11). The emphasis of instruction was on *fast*, but subjects also were encouraged to reach a peak torque of at least 65% MVC. Before each attempt, the subjects were asked whether they were ready. After confirmation, data sampling was started, and the subject had to make the attempt within 10 s after confirmation but could otherwise choose his own start.

Before each contraction, the 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. Between the contractions, there was 2 min of rest. Finally, three twitches (sampled at 5 kHz, with 1.5 s in between) were applied to the knee extensors to obtain M-waves for EMG normalization.

Data Analysis

Torque. Torque and EMG signals were sampled at 2 kHz and analyzed with custom-written software using Matlab version 6.5 (The MatWorks, Inc. Natick, MA). Torque signals were filtered using a fourth-order Butterworth 150-Hz low-pass filter. To enable comparison of fast isometric contractions between our previous (11,12) and present experiments, torque–time integral for the first 40 ms (TTI40) after the onset of torque development was calculated for voluntarily and electrically evoked contractions. In addition, the maximal rate of torque development (MRTD) during electrically stimulated (octet) and maximal voluntary contractions was calculated. MRTD was taken as the maximum of the differentiated filtered torque signals. Time to MRTD was defined as the time from torque onset to the moment at which MRTD was reached.

Baseline fluctuations (50-Hz signal noise) of the filtered torque were < 0.1 N·m around zero. During octet stimulation and the maximal voluntary contractions, onset of torque development (start of torque rise) was defined as the point at which the first derivative of the filtered torque signal crossed zero for the last time before torque rise. With this criterion, the start of torque development can be determined even more precisely, as with our previous criterion (11). Before contraction onset, leg muscles had to be completely relaxed: we did not want any countermovement or pretension before contraction onset. We used the following objective procedure to check for nonrandom torque fluctuations before contraction onset. Immediately after a contraction, a linear regression line was fitted through the baseline filtered torque signal for 100 ms before onset of torque development (defined in the above). A positive slope of the torque signal before onset of torque development indicated that the knee extensors were not fully relaxed before torque onset (pretension), which was

TABLE 2. Electrically elicited contractile characteristics (eight pulses at 300 Hz).

	Day 1	Day 2	ICC	P	η^2	Average
Peak torque (N·m)	191 ± 25	196 ± 21	0.96*	0.08	0.28	194 ± 24
Time to maximal rate of torque development (ms)	51 ± 8	51 ± 8	0.81*	0.80	0.007	51 ± 7
Maximal rate of torque development (N·m·s ⁻¹)	4672 ± 1274	4832 ± 1261	0.79*	0.63	0.03	4752 ± 1153
TTI40 (N·m·s)	0.76 ± 0.22	0.74 ± 0.23	0.85*	0.75	0.01	0.75 ± 0.21

* Significant ($P < 0.05$) intraclass correlation coefficient (ICC), P value, and size effect (η^2) between days, average value across days.

generally confirmed by very low levels of knee-extensor EMG activity. A negative slope was seen during attempts where a very small countermovement was visible in the torque signal just before torque onset. The absolute slope of the regression line had to be less than 1.5 N·m·s⁻¹; otherwise, the attempt was discarded. The slope limit of 1.5 N·m·s⁻¹ was determined during hundreds of pilot measurements, which showed that values of voluntary TTI40 and MRTD increased significantly if, immediately before a maximal voluntary contraction, absolute slope became > 1.5 N·m·s⁻¹.

EMG. EMG signals were corrected for offset, filtered using a unidirectional, zero-phase lag high-pass (5 Hz) second-order Butterworth filter, and rectified. Knee-extensor EMG signals were normalized to the peak to peak amplitude of the M-wave (averaged for three twitches) in each subject. Biceps femoris EMG was normalized to the EMG (averaged for 500 ms) obtained during the highest maximal flexion MVC.

As an indication of voluntary activation at the very start of muscle contraction, rectified and normalized surface EMG signals obtained during maximal voluntary contractions were averaged for 30 ms before the onset of torque development to 10 ms after torque onset (EMG40). This interval was chosen to couple activation to TTI40, assuming an electromechanical delay (EMD) of 30 ms. Even in “slow” subjects, we never have seen any EMG activity before 30 ms of torque onset (12), and during electrical stimulation (with a very steep torque onset), EMD is even shorter (11).

Similar to our previous studies (11), variation in EMG40 among the three different knee-extensor muscles was seen between different attempts, but no significant differences were found among the muscles. Therefore, after filtering and rectification of the signals for each muscle, the average

values of the knee-extensor muscles were calculated as indication of voluntary muscle activation. EMG of the long head of the biceps femoris muscle was sampled as an indication of cocontraction during knee extensions. However, similar to our previous studies, cocontraction was found to be very low and comparable with our previous results; therefore, these data will not be presented (11).

Statistics. The results are presented as mean values ± SD. The statistical analysis was done using SPSS version 11.5 (SPSS Inc., Chicago, IL). The test–retest reliability between the two sessions was analyzed using the intraclass correlation coefficient (ICC). Student’s paired t -tests were used to establish significance ($P \leq 0.05$) between measurements made on both days; effect sizes (partial η^2) are also reported. Unless indicated otherwise, for each subject the mean value of the best attempts (highest values) on both days are presented and used to establish significance ($P \leq 0.05$) of correlation between parameters using Pearson’s correlation coefficient.

RESULTS

Reproducibility of electrically evoked contractions. The reproducibility of the electrically induced contractions (octet stimulation) across days was high for the peak torque reached during these short, maximal contractions (Table 2). However, reproducibility was somewhat lower for the measures of torque development, although the average values for the parameters were very similar ($P > 0.05$) across days (Table 2). To reduce variability, for each subject the average value for both days was taken to characterize the isometric contractile speed of his knee-extensor muscles under conditions of maximal activation (eight pulses at 300 Hz).

TABLE 3. Contractile characteristics of knee extensors during voluntary effort and jump performance.

	Day 1	Day 2	ICC	P	η^2	Average
Maximal voluntary contraction (N·m)	317 ± 76	371 ± 83*	0.97†	< 0.01	0.80	344 ± 75
Maximal torque capacity (N·m)	395 ± 46	408 ± 71	0.88†	0.29	0.11	402 ± 54
Voluntary activation (%)	80 ± 13	91 ± 8*	0.82†	< 0.01	0.65	85 ± 10
EMG40/M-wave amplitude	1.69 ± 1.40	1.85 ± 1.55	0.85†	0.68	0.02	16 ± 12
Fast peak torque (N·m)	241 ± 58	250 ± 56	0.93†	0.35	0.09	245 ± 55
Time to maximal rate of torque development (ms)	76 ± 19	82 ± 28	0.87†	0.25	0.13	79 ± 22
Maximal rate of torque development (N·m·s ⁻¹)	2891 ± 1204	2711 ± 1312	0.85†	0.53	0.04	2801 ± 1174
TTI40 (N·m·s)	0.18 ± 0.09	0.18 ± 0.11	0.91†	0.96	< 0.01	0.18 ± 0.10
SJ120 (cm)	34.6 ± 5.0	35.3 ± 4.3	0.90†	0.43	0.07	35.0 ± 4.4
Countermovement jump (cm)	47.4 ± 6.4	47.8 ± 5.4	0.97†	0.54	0.04	47.6 ± 5.8
Countermovement jump with arm support (cm)	61.1 ± 5.7	61.0 ± 6.0	0.99†	0.71	0.02	61.1 ± 5.8

EMG40, electromyographic signals obtained during maximal voluntary contractions, averaged for 30 ms before the onset of torque development to 10 ms after torque onset; TTI40, torque time integral for the first 40 ms after torque onset; SJ120, squat jump from 120° knee angle.

* Significantly different from day 1; † significant ($P < 0.05$) intraclass correlation coefficient (ICC), P value, and size effect (η^2) between days, average values across days.

TABLE 4. Individual contractile parameters during electrically evoked and fast voluntary knee extensions (average values across 2 d).

Subject	Electrically Evoked (Eight pulses at 300 Hz)				Voluntary Attempts		
	MRTD (N·m·s ⁻¹)	MRTD (%MTCms)	Time to MRTD (ms)	TTI40 (N·m·s)	MRTD (N·m·s)	Time to MRTD (ms)	TTI40 (N·m·s)
1	3620	1.25	52	0.43	3254	54	0.39
2	5062	1.11	56	0.91	4939	84	0.16
3	4866	1.16	36	1.06	1389	131	0.07
4	4711	1.15	51	0.82	3890	60	0.18
5	6773	1.64	39	0.98	2030	82	0.13
6	6164	1.75	49	0.78	1556	72	0.22
7	3425	0.77	52	0.73	1875	90	0.08
8	3281	0.85	57	0.39	2291	90	0.04
9	4271	1.24	56	0.57	2476	92	0.08
10	4188	0.86	57	0.83	2742	55	0.32
11	5909	1.47	54	0.74	4372	62	0.26
Mean	4752*	1.20	51*	0.75*	2801	79	0.17
SD	1152	0.32	7	0.21	1174	22	0.11

MRTD, maximal rate of torque development; MTC, maximal torque capacity; TTI40, torque time integral for the first 40 ms after torque onset.

* Significantly different from the voluntary contractions.

Reproducibility of voluntary contractions.

Reproducibility for maximal voluntary isometric contractions (Table 3) was high across days, although MVC and maximal voluntary activation (VA) during MVC were significantly higher on the second day. However, as would be expected, MTC was not different across days (Table 3). Therefore, the average value for MTC in each subject was used to quantify the maximal possible torque (MTC) of his knee extensors under conditions of full activation—that is, when VA would have been 100% in each subject. The linear extrapolation used to determine MTC (Fig. 1) was reliable in that r^2 ranged from 0.88 to 0.99 (0.95 ± 0.04).

The parameters related to the explosive isometric contractions (Table 3, rows 4–8) and jump height (Table 3, bottom three rows) were very similar across days ($P > 0.05$), and reproducibility was good. Nevertheless, and similar to the electrically evoked contractions, the average value for both days was used for each subject, to reduce variability and to provide a better representation of the true scores involving the parameters obtained during voluntary effort (e.g., with jump height and with parameters determined during electrical stimulation).

Isometric torque. Table 1 shows that the subject group was rather homogenous in terms of body measures and maximal isometric torque production of the knee extensors and flexors. Notable is the variation in maximal voluntary activation during isometric knee extensions, which ranged from 69% in subject 3 to 99% in subject 11.

Maximal torque development. Despite of the short duration of the stimulus train (eight pulses at 300 Hz = 23 ms), peak torque reached during the maximal electrically evoked knee extensions was 198 ± 22 N·m, which still was $49 \pm 5\%$ of the calculated MTC of the knee extensors. During the voluntary contractions, the peak torque reached was $61 \pm 10\%$ of MTC.

The individual data for MRTD, time to MRTD, and TTI40 are shown in Table 4. MRTD obtained during electrical stimulation (4752 ± 1153 N·m·s⁻¹) was significantly

cantly higher than MRTD during voluntary contractions (2801 ± 1174 N·m·s⁻¹, $P = 0.002$, $\eta^2 = 0.62$). Moreover, time to MRTD was shorter ($P = 0.005$, $\eta^2 = 0.55$) in electrically evoked (51 ± 7 ms) than in the voluntary attempts (79 ± 22 ms). This also was clearly reflected in the torque–time integral calculated for the first 40 ms after torque onset (TTI40), which was about fourfold greater during stimulated (0.75 ± 0.21 N·m·s) compared with voluntary contractions (0.17 ± 0.11 N·m·s, $P < 0.001$, $\eta^2 = 0.85$). TTI40 during maximal voluntary contractions was only $25 \pm 22\%$ of the maximal possible TTI40 obtained during electrical stimulation. Subject 1 was the only subject who, during voluntary attempts (TTI40 = 0.39 N·m·s), approached the TTI40 value his knee extensors could deliver when they were maximally activated during electrical stimulation (0.43 N·m·s). Figure 2A shows examples of torque development of subject 1 compared with those of an average subject (subject 4). Note the clear difference between both subjects during voluntary effort, whereas torque development during maximal electrical stimulation is very similar. Also note that high peaks in the EMG of subject 1 are visible immediately before voluntary torque onset in Figure 2B, whereas subject 4 shows a more gradual increase of EMG.

During voluntary contractions, there was no direct relation between TTI40 and MRTD ($r = 0.38$, $P = 0.30$). However, there was a significant negative linear relation between TTI40 and time to MRTD ($r = -0.80$, $P = 0.003$). Time to MRTD was not significantly ($r = -0.51$, $P = 0.11$) related to MRTD.

There were strong positive linear relations ($r > 0.86$) between EMG40 and voluntary TTI40 (Fig. 3). Neither MRTD nor TTI40 obtained during voluntary contractions were significantly related to their respective values obtained during electrical stimulation ($r = 0.05$, $P = 0.89$; $r = -0.19$, $P = 0.57$). Electrically evoked TTI40 was significantly related to MTC ($r = 0.62$, $P = 0.04$), but stimulated MRTD ($r = 0.07$, $P = 0.83$), voluntary MRTD ($r = 0.16$, $P = 0.65$), and voluntary TTI40 ($r = -0.20$, $P = 0.61$) were not related to MTC.

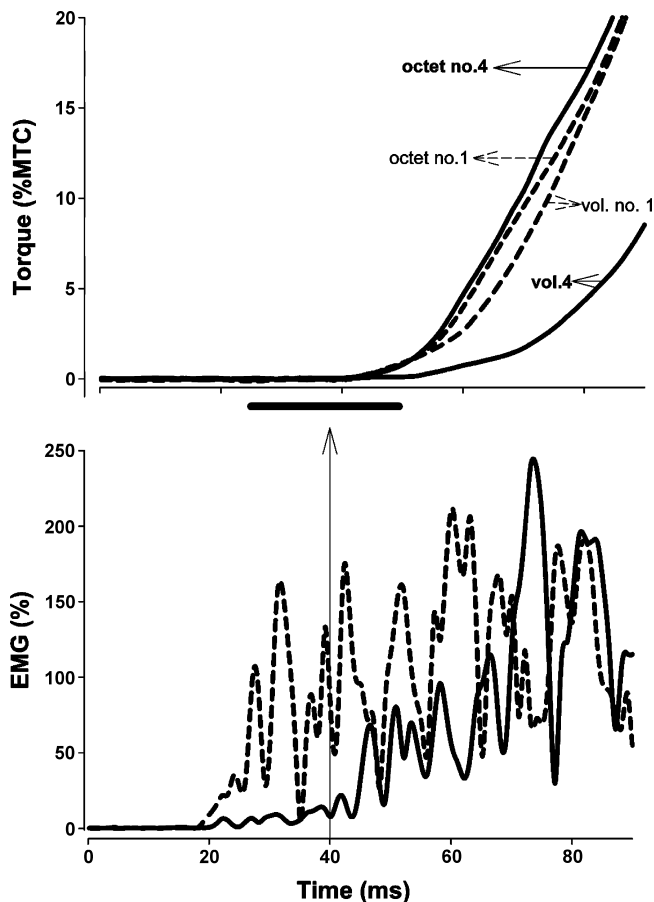


FIGURE 2—Normalized torque (*top*) and EMG (*bottom*) signals of maximal voluntary isometric contractions (vol.) and electrically evoked contractions (octet) of subject 1 (*dashed traces*) and subject 4. The rectified surface EMG signals (normalized to EMG during MVC) of the knee extensors are only shown for the voluntary contractions. Note that torque increase is similar for both subjects during electrically evoked contractions, but that subject 1, whose EMG starts with high peaks, is much faster during voluntary contractions. In this example, voluntary TTI40 of subject 1 is 79% of the electrically evoked TTI40 (*dashed torque traces* run close together), whereas for subject 4 this was 19%, which is about the average of the other subjects. The signals are synchronized at torque onset as indicated by the *arrow* at 40 ms. The electrical stimulation is indicated by the *horizontal bar* beneath the top x-axis.

Jump performance. As was to be expected, jump height during jumps with countermovement from a freely chosen knee angle and with arm support were significantly higher than the countermovement jumps without arm support, which, in turn, were significantly higher than the

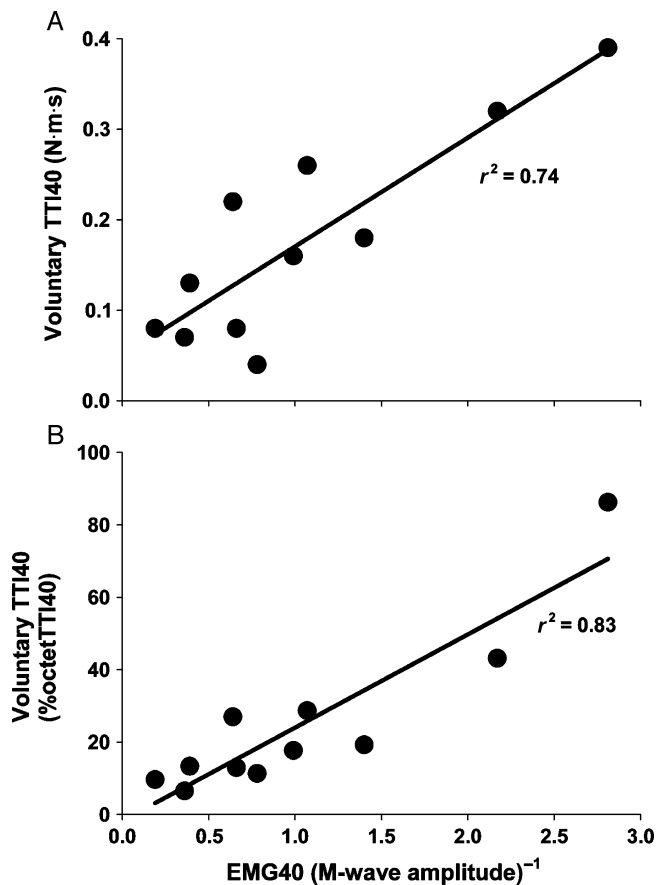


FIGURE 3—Torque–time integral for the first 40 ms of maximal voluntary contractions (TTI40) as a function of rectified and averaged knee-extensor surface EMG (normalized to M-wave amplitude) calculated from 30 ms before (electromechanical delay) until 10 ms after torque onset (EMG40). Absolute values of voluntary TTI40 are presented (*A*), and voluntary TTI40 is also shown as a percentage of the electrically evoked TTI40 (*B*).

SJ120 (Table 3). Height obtained during SJ120 was significantly related to the other jumps ($r = 0.75$ and 0.72 for countermovement jumps without and with arm support, respectively), but the correlation coefficient between both countermovement jumps was higher ($r = 0.89$; $P \leq 0.05$).

Contractile properties and jump height. There were no significant relations between jump height and MTC ($r < 0.28$) or MVC ($r < 0.48$) for any of the three jumps. MRTD during stimulated contractions was the only parameter that had a significant relation with jump height

TABLE 5. Correlations between contractile properties and jump height.

Jump (<i>N</i> = 11)	Electrically Evoked				Voluntary Attempts			
	MRTD	MRTD (%MTC)	Time to MRTD	TTI40 (N·m·s)	MRTD	Time to MRTD	TTI40 (N·m·s)	TTI40 (%MTC)
Squat jump from 120° knee angle	0.84*	0.75*	-0.29	0.48	-0.09	-0.13	0.15	0.003
Countermovement jump without arm support	0.71*	0.52	-0.17	0.40	0.31	-0.16	0.22	0.07
Countermovement jump with arm support	0.59†	0.43	0.14	0.21	0.44	-0.55	0.43	0.22

* $P < 0.05$; † $P = 0.06$.

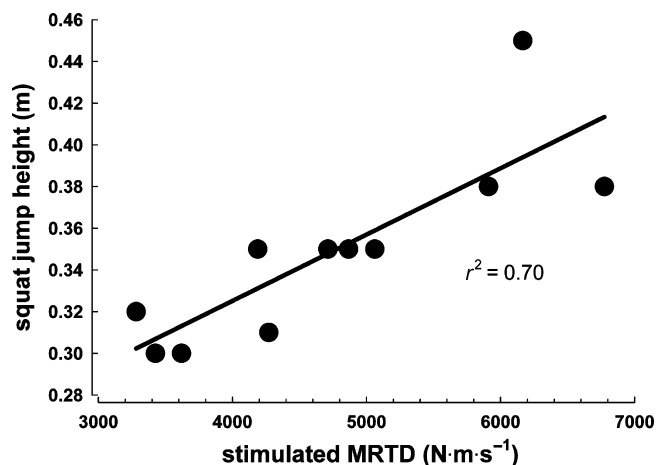


FIGURE 4—Squat jump height as a function of the maximal rate of torque development obtained during electrical stimulation (eight pulses at 300 Hz).

(Table 5, Fig. 4). For SJ120, this relation was also significant when data for both days were analyzed separately. Unexpectedly, none of the parameters obtained during voluntary contractions was significantly related to jump height (Table 5). In addition, there were no significant correlations ($r < 0.02$) between EMG40 and jump height for any of the three jumps.

DISCUSSION

Within a group of similarly trained good jumpers, unilateral voluntary isometric torque development was found to be related to the neural drive generated by the subjects at the start of the contraction but not to the knee-extensor contractile properties obtained during maximal electrical stimulation. However, in contrast with our hypothesis, only the maximal rate of torque development obtained during electrical stimulation and not the ability for fast voluntary contractions could predict jump height in the present group of young male elite volleyball players.

In the present subject group, the ability to achieve a steep rise of torque at contraction onset was almost completely dependent on the ability to generate high initial peaks in the EMG at the start of these explosive contractions: up to 83% of the variance in TTI40 could be accounted for by the differences in EMG40 at the start of the contraction (Fig. 3). This percentage is even higher than the 75% (11) and 64% (12) we have reported previously in young and healthy, but less trained, males. In addition, and somewhat to our surprise, the ability for voluntary torque development in the present subjects was not very high. On average, voluntary TTI40 was only 25% of the maximal possible TTI40 as established during electrical stimulation, which is rather low compared with the 40% we found in our previous study with less trained subjects of the same age (11). There was only one player (subject 1) who, during voluntary contractions, approached his muscles' maximal

capacity for torque development. Together, these findings suggest that the volleyball players can improve the early phase of torque development of their knee extensors considerably by improving muscle activation.

Despite the large influence of muscle activation on voluntary torque development in the dynamometer, it is rather surprising that voluntary TTI40 and MRTD in the present study and in our previous study (9) did not tend to be related to electrically evoked torque development ($r^2 < 0.04$). It may be speculated that muscle activation during maximal voluntary isometric knee extension is such a dominating factor with respect to maximal torque development that properties of the muscle tendon complex (e.g., fiber type composition, tendon stiffness) are less important during this task, at least in the present group of well-trained volleyball players. In conflict with the present findings, Andersen and Aagaard (2) have shown that the rate of knee-extensor torque development during twitch stimulation and voluntary effort were moderately ($r^2 = 0.36$) but significantly related. However, they used twitch surface stimulation, resulting in an approximately sevenfold less steep MRTD compared with the maximal nerve stimulation (eight pulses at 300 Hz) applied in the present study. Maximal activation at high stimulation rates is necessary to obtain the maximal rate of torque development of skeletal muscle, probably because it is only in this manner that maximal saturation levels of intracellular calcium are achieved (10,27). Consequently, the relative importance of possible factors that affect MRTD, such as Ca^{2+} kinetics, cross-bridge cycling rate, and tendon stiffness, may differ between twitch and octet stimulation.

During electrical stimulation, the range in MRTD, even after normalization to MTC, was substantial (0.77–1.75% MTC per millisecond) and correlated significantly with jump performance (Fig. 4, $r^2 = 0.70$). Isometric contractile speed and jump performance have been related to the percentage of type II muscle fibers (7,17) and tendon stiffness (6,23). Unfortunately, because we could not take any muscle biopsies in these elite sportsmen and we did not measure tendon stiffness, we do not know the contribution of both factors to the differences in electrically evoked MRTD and jump performance among the present subjects.

In accordance with other studies, jump height was not related to knee-extensor MVC (or MTC) (3,18,30). However, jump performance clearly was related to stimulated MRTD ($r = 0.84$), but stimulated MRTD and MTC were not significantly related ($r = 0.21$). These findings suggest that maximal contractile speed is more important for good jump performance than maximal torque.

In contrast to our recent findings and our hypothesis, voluntary TTI40 was not related to jump performance (12). There are obvious differences between unilateral isometric knee extension and jumping, and for that reason it has been argued that isometric measures can not predict performance during more complex dynamic movements (4,26). Moreover, about 60% of the work done during a jump is

produced by muscles other than the knee extensors (5). Nevertheless, we recently have found good correlations between the ability for voluntary isometric knee-extensor torque development (TTI40) and jump performance (e.g., $r^2 = 0.71$ for SJ120) in normal, healthy subjects (12). In that study, and similar to the present study, voluntary TTI40 was highly dependent on EMG40, and during jumping the rise in ground-reaction force was significantly related to the amplitude of the preceding EMG. At the time, we concluded that a high efferent neural drive seemed important not only for torque development during unilateral voluntary isometric knee extension but also for jumping (12). Unfortunately, in that study we did not apply octet stimulation, and thus isometric torque development of the muscles during maximal activation was unknown (12). Compared with that study, the present group of subjects was more homogenous with respect to training status, jumping experience, and voluntary TTI40 (which was generally low in the subjects of the present study). These factors may have contributed to the nonsignificant correlation between voluntary TTI40 (or EMG40) and jump height in the present study.

It is well known that voluntary rate of torque development can be increased by improving the efferent neural drive to the muscles at torque onset (1,16,27). Moreover, intrinsic muscle speed and jump performance are positively related to the percentage of type II muscle fibers (7,17). It is also known that jump performance can be increased by specific training (19). However, the potential contributions of improved muscle activation and other factors, such as training-induced increases in fast muscle fiber cross-sectional area (8,16), to jump improvement remain to be established.

In conclusion, in the present group of elite young male volleyball players the only parameter measured in the dynamometer during unilateral isometric contractions that could convincingly predict bilateral jump performance was the maximal rate of knee-extensor torque development obtained during electrical stimulation. Although care has to be taken when interpreting correlations between parameters, the present findings suggest that intrinsic contractile speed of the muscles dominates jump performance in skilled jumpers.

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