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ORIGINAL ARTICLE

Leg dominancy in relation to fast isometric torque production and squat jump height

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Abstract We hypothesized that maximal unilateral isometric knee extensor torque, the rate of torque development during maximally fast isometric contractions and unilateral squat jump performance would be better with the dominant than non-dominant leg. Limb dominancy was established using the step up, balance recovery, and ball kick test. On two days, eight men (21.5 ± 2.2 years, means ± SD) performed unilateral maximal isometric contractions with their knee extensors (120° knee angle) with superimposed electrical stimulation to determine maximal torque and voluntary activation for both limbs. In addition, maximally fast isometric contractions without countermovement and unilateral squat jumps (SJ) starting from 120° knee angles were performed. Torque time integral (contractile impulse) over the first 40 ms after torque onset (TTI40) and maximal rates of torque development (MRTD) during voluntary and maximal electrical nerve stimulation were used to quantify initial torque rise. Limb dominancy tests were very consistent, but none of the parameters was (or tended to be) significantly different between limbs, neither during maximal electrical stimulation nor during voluntary attempts. Between limbs there were significant relationships for voluntary TTI40 ($r^2 = 0.94$) and maximal SJ height ($r^2 = 0.88$) and both parameters were significantly related in both limbs ($r^2 = 0.69$ and 0.75). In conclusion, unilateral fast torque generating capacity, muscle activation and squat jump performance were similar in both limbs, but differed substantially among subjects, with strong correlations between fast voluntary isometric torque development and jump height. These findings further challenge the concept of lower limb dominancy in dynamometry testing in sports and rehabilitation.

Keywords Electrical stimulation · Voluntary muscle activation · Torque rise · Rate of force development

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Introduction

In (neuro) physiological experimentation and rehabilitation it is common practice to indicate whether a certain task or test was performed with the dominant or the non-dominant limb. Especially in relation to upper limb motor tasks, clear differences between for instance dominant and non-dominant hands have been reported in performance and the related activity in different parts of the brain (Kapreli et al. 2006). Also for lower limb exercise, for example for one legged dynamometry tests, in the majority of studies it is reported whether the dominant or the non-dominant leg was involved. This suggests that it is, similar to upper limb tasks, important to take limb dominancy into account when studying lower limb motor performance in the dynamometer. Consequently, for one legged exercise testing and regardless the task at hand, limb dominancy usually is reported. Lower limb dominancy is often established by asking subjects which leg is their preferred kicking leg or with the use of some simple standardized tests, among which the balance recovery and the step up test are most commonly used (e.g., Hoffman et al. 1998; Lin et al. 2009). The (implicit) assumption usually is that performance would be better with the dominant leg. For example during unilateral leg dynamometry, which is often used in clinical- and sport-related research, subjects are assumed to be stronger or more powerful with their dominant than their non-dominant leg. However, there are many indications in the literature that for several unilateral lower limb tasks such as static balance control (Hoffman et al. 1998; Lin et al. 2009), unilateral squatting exercise (McCurdy and Langford 2005), isokinetic knee extensor strength and jumping (Ostenberg et al. 1998), performance may not systematically be better with the dominant leg compared to the non-dominant leg. These findings question the usefulness and importance of reporting leg dominancy as derived from standard tests during lower limb dynamometry.

Maximal isometric torque production has also been shown not to differ between the ‘dominant’ and ‘non-dominant’ leg, but in the same subjects torque exerted during isokinetic leg extensions was found to be higher in the dominant versus the non-dominant leg (Hotta et al. 2007). However, this is not a general finding, not even in soccer players with clear leg preferences (Masuda et al. 2005; Mognoni et al. 1994; Zakas 2006).

Differences in maximal torque production between legs may be due to differences in muscle mass and contractile properties (fiber type composition, muscle architecture) and/or differences in maximal neural activation. The latter was found to be similar at the torque plateau during maximal isometric knee extension effort between the preferred kicking leg and the contralateral leg in non-soccer players (Guette et al. 2005). However, potential differences in ability to maximally activate the knee extensors of the dominant versus the non-dominant leg during short lasting fast ‘explosive’ torque production have, to our knowledge, not been investigated. Many movements are characterized by a short execution time and therefore available time for muscle force generation is often less than 200 ms (Kuitunen et al. 2002). Consequently during sprinting, jumping, and balance recovery, fast torque development may be more important than the maximal isometric torque, which usually is only reached after about 1 s of muscle activity. Fast voluntary torque generation critically depends on the magnitude of neuromuscular activity (EMG) at contraction onset (Van Cutsem et al. 1998; de Ruiter et al. 2004a, b; Del Balso and Cafarelli 2007), which was found to be positively related to jump performance (de Ruiter et al. 2006).

The goal of the present study was to investigate whether the ability for a fast onset of neural activation during isometric leg extension and one-legged squat jump height differed between the dominant and the non-dominant leg. Maximal voluntary rate of torque development was compared with electrically elicited torque development. This was done to investigate whether potential differences between legs would be due to properties of the muscle tendon complex (assessed with maximal electrical stimulation of the femoral nerve) or would be caused by side specific differences in the ability of subjects to voluntarily recruit their muscle fibers. We hypothesized that maximal isometric knee extensor torque, the rate of torque development and one-legged squat jump height would be greater in the dominant than the non-dominant leg, when dominancy was established with commonly used standard tests.

Materials and methods

Subjects

Eight healthy male subjects (Table 1) signed informed consent and the local ethics committee approved the study. The subjects came to the lab two times with 2–6 days in between sessions, which lasted about 2 h each.

Isometric torque measurement

Contractile properties of the knee extensors of the both legs were investigated using a custom made dynamometer used in previous studies (de Ruiter et al. 2004a, b, 2006, 2007). 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 25 cm distally from the knee joint, which measured the force exerted at the shin. The real-time force applied to the force transducer was displayed online on a computer monitor and digitally stored (2,000 Hz). The force signals were corrected for gravity. Extension torque was calculated by multiplication of force with the 25 cm lever arm.

To minimize the dampening effect that exists in any interface between shin and aluminum transducer, but to

Table 1 Subject characteristics

No.	Age (yr)	Mass (kg)	Height (cm)	Sports	Hours/week
1	20	80	195	Baseball	16
2	20	73	185	Judo, gymnastics	7.5
3	21	75	180	None	0
4	19	72	180	Fitness, running	9
5	26	70	186	400–800 m run	12
6	22	68	178	Volleyball	3
7	23	83	176	Cycling, running	6
8	21	69	184	None	0

simultaneously avoid pain, this 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, this strap was released between contractions. Measurements were made at the 120° knee angle (180° indicates straight leg), because this is the angle at which maximal torques are produced during isometric knee effort (de Ruiter et al. 2004a, b). Moreover, although the magnitude of neuromuscular activity (EMG) at contraction onset was found to vary considerably among subjects, it was independent of knee angle (de Ruiter et al. 2004a, b). The compliance of the dynamometer at the position of the transducer was 1.4×10^{-4} deg $(\mathrm{Nm})^{-1}$. The 120° knee angle was set with the use of a handheld goniometer and anatomical landmarks (trochanter major femoris, epicondylis lateralis, and malleolus lateralis on the fibula) while subjects performed a voluntary contraction of about 50% maximal isometric voluntary contractile strength (MVC). This was done to correct for unavoidable changes (3–7°) in knee angle which always occur when knee extensor muscles go from the passive into the active state (de Ruiter et al. 2004a, b). Thus the 120° knee angle is an active knee angle and the axis of rotation of the knee was aligned with the axis of rotation of the dynamometer with active knee extensors.

Electrical stimulation

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 each 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 activated (e.g., Fig. 1, de Ruiter et al. 2008). Triplet stimulation was used to calculate maximal voluntary activation during MVC (see below). In addition, short bursts of eight pulses (octet stimulation) at 300 Hz were applied at rest to obtain the maximal possible rate of torque development of the knee extensors (de Ruiter et al. 2004a, b, 2007).

Jump height

One legged squat jumps starting from the 120° knee angle (SJ120) were performed. 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 an upright upper body and with their hands on their hips. While standing in the correct jump position a metal rod of 1.5 m length was placed horizontally 1 cm underneath the subjects' buttocks. Subjects had to jump without touching the metal rod, thus 'countermovement' was <1 cm, which has been shown not to enhance SJ performance (Hasson et al. 2004). If the buttocks contacted the rod during push off, signifying a considerable countermovement, the jump was discarded. The contralateral leg was held anterior to the jump leg and remained 'passive' with the foot just above the ground at the start of the jump. Subjects were encouraged to jump as high as possible without using their contralateral leg and arms. Jump height measured with a simple device (basically a tape measure, which slid between two small messing plates between the feet in the floor when subjects jumped) with good reproducibility (ICC = 0.94) validated with a 3D camera system (Optotrak, type 3020, Northern Digital inc., Waterloo, ON, Canada) sampled at 200 Hz (de Ruiter et al. 2007), there was a strong significant linear relationship between jump height determined with both methods ($r^2 = 0.997$, $y = 1.00x + 0.0017$).

Leg dominancy

Three standard tests, which are often used to determine leg dominancy, were used in the present study. At the start of the first session subjects were asked to step up a platform (40 cm); the leading leg spontaneously chosen by the subject was considered the dominant leg. Moreover, while standing erect with parallel feet subjects were forcefully pushed from behind between the shoulder blades and the leg with which they stepped out to prevent a fall was considered the dominant leg. In addition, subjects were asked with which leg they preferred to kick a ball. In this case, the kicking leg was considered the dominant leg. In the present study, the dominant leg was defined as the leg that was dominant in at least two of the three tests. To check for consistency the step test and the balance recovery test were repeated in between the dynamometer tests of both legs and again at the end of the first session.

Protocol

The dominant leg was tested first in half of the subjects (Table 1; no. 1, 3, 5, 7) in the other subjects the non-dominant leg was tested first. This pattern was repeated on the second-day. All subjects first performed the jump tests followed by the dynamometry. After a warming up which consisted of a series of 10 jumps per leg (alternating) with increasing intensity, and following 2 min rest, subjects performed three maximal SJ120 with 30 s rest in between with each leg. Thereafter the subjects were accompanied to the dynamometer, which was in another laboratory room and allowed a 10 min rest to minimize any potential fatiguing effects of the jumps on the subsequent dynamometer tests. Dynamometry started with approximately five isometric contractions at about 50% MVC which were needed to set the lever arm such that the correct knee angle of 120° was obtained during contraction. Thereafter, the stimulation current was increased in five to seven steps until maximal activation was reached, which was until no further increase of torque in response to triplet-stimulation occurred. Together the aforementioned contractions served also as specific warm-up for the dynamometry tests. The actual measurements consisted of five maximal voluntary knee extensions which were made under strong verbal encouragement and with online visual feedback with 4 min rest in between. When a few seconds into the contraction torque had leveled off, maximal triplet stimulation, manually triggered by one of the investigators, was superimposed upon the MVC. Thereafter the subjects were instructed to relax completely and after about 5 s an additional triplet was applied on the relaxed muscle. These measurements were used to establish maximal voluntary activation (VA) and maximal torque capacity (MTC) of the knee extensors (see "Data analysis").

The MVCs were followed by application of two short electrical bursts of 8 pulses applied at 300 Hz (octet stimulation) on a fully relaxed muscle with 2 min rest in between. These octet stimulations were applied to determine the muscles' maximal capacity for isometric torque development during full maximal activation (de Ruiter et al. 2004a, b, 2007).

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 with 1 min rest in between (de Ruiter et al. 2004a, b, 2007). The emphasis of the instruction was on fast: maximal rates of torque development cannot be obtained when subjects try to reach maximal isometric torques levels. Before each attempt the subjects were asked if they were ready and following confirmation, data sampling was started and subjects had to make the attempt within the following 10 s.

Subjects were encouraged to try to make use of the muscles' full capacity for torque development as assessed with the foregoing octet stimulation. Torque time integral over the initial 40 ms (contractile impulse) of the contraction (TTI40, see below) was provided as feedback and compared with TTI40 obtained during the foregoing octet stimulation. Attempts preceded by pretension or a counter movement were discarded (see "Data analysis"). Usually about 8 eight attempts were necessary to obtain five valid attempts.

Data analysis

Torque

Torque signals were sampled at 2 kHz and analyzed with custom written software using Matlab version 6.5 (The MatWorks, Inc., Natick, Massachusetts). Torque signals were filtered using a fourth order Butterworth 150 Hz low-pass filter. To enable comparison of fast isometric contractions between our previous (de Ruiter et al. 2004a, b, 2006, 2007) and present experiments, torque time integral over 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 Nm around zero. 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 (de Ruiter et al. 2007). Prior to contraction onset leg muscles had to be completely relaxed: without any counter-movement or pre-tension before contraction onset. We used the following objective procedure to check for non-random torque fluctuations before contraction onset. Immediately following a contraction a linear regression line was fitted through the baseline filtered torque signal over 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 prior to torque onset (pre-tension), which in previous studies was confirmed by very low levels of knee extensor EMG activity (de Ruiter et al. 2004a, b). A negative slope was seen during attempts where a very small 'countermovement' was visible in the torque signal just prior to torque onset. The absolute slope of the regression line had to be less than 1.5 Nm s^{-1}, otherwise the attempt was discarded. The slope limit of 1.5 Nm s^{-1} was used in a previous publication (de Ruiter et al. 2007) and was originally determined during hundreds of pilot measurements, which showed that values of voluntary TTI40 and MRTD increased significantly if immediately prior to a maximal voluntary contraction absolute slope became >1.5 Nm s^{-1}. This additional check for unwanted small countermovements resulted in a very reliable and sensitive method for torque onset detection; torque at the contraction onset was <0.1 Nm (~0.04% MVC).

The subjects' ability for maximal voluntary activation (VA) during an MVC of several seconds duration was assessed using the following calculation: VA = 1 − [triplet amplitude at MVC · (triplet amplitude at resting muscle)$^{-1}$] · 100% (de Ruiter et al. 2004a, b, 2006). From the attempt with the highest value of VA (the highest MVC), maximal torque capacity (MTC) of the knee extensors was calculated using: MTC = (Maximal voluntary torque) · (VA)$^{-1}$ · (100%)$^{-1}$ (de Ruiter et al. 2004a, b, 2006). MTC is an estimate of the maximal isometric torque under conditions of maximal muscle activation. The most direct way to assess MTC would be 500–1,000 ms of maximal tetanic nerve stimulation (150 Hz), however, this is very stressful, unpleasant, and may even be harmful. Therefore, tetanic nerve stimulation is not an option to assess MTC of the knee extensors.

Because the parameters of fast torque development are very sensitive (subtle differences in torque rise have substantial effects on TTI40 and MRTD), we decided to use the averaged values of the two best attempts for each leg on both days. In addition, for each day the responses to both burst of octet stimulation and also the two highest jumps recorded for each limb were averaged.

Statistical analysis

The results are presented as mean values ±SD. The statistical analysis was done using SPSS version 16.0 (SPSS Inc., Chicago, USA). To test for significant ($P < 0.05$) differences between days and limbs a repeated measures (day and limb) ANOVA was used and effect sizes (partial η^2) were reported. For the parameters of torque development 'stimulation' (voluntarily or electrically) was added as a third factor. Note that, in order to increase reliability of the data, for the parameters of fast torque development as well as for jump height, for each subject the average value of the two best attempts on each day was used in the repeated measures ANOVA. The test–retest reliability between the two sessions was analyzed using the intraclass correlation coefficient (ICC). The coefficient of variation (CV) was defined as the (SD/mean) · 100% for each subject; subsequently the group average values (±SD) were calculated. Significance ($P < 0.05$) of correlation between parameters of fast voluntary torque development and jump height was established using Pearson's correlation coefficient, using the average values of four attempts (the two best attempts on each day).

Results

The outcome of the three tests for dominancy (Table 2) was surprisingly consistent: for two subjects (1 and 8) the left leg was found to be the dominant leg, for the others clearly it was the right leg.

Table 2 Leg dominancy tests

No.	Step up			Balance recovery			Ball kick	Overall dominancy
	1	2	3	1	2	3		
1	L	L	L	L	L	L	L	L
2	R	R	R	R	R	R	R	R
3	R	R	R	R	R	R	R	R
4	R	R	R	R	R	R	R	R
5	R	R	R	R	R	R	R	R
6	R	R	R	R	R	R	R	R
7	R	L	R	R	R	R	R	R
8	L	L	L	L	L	L	L	L

L and *R*, respectively, denote dominant Left or Right limb

For none of the parameters investigated significant differences were found between days. There were no significant differences between the limbs with respect to MVC strength ($P = 0.507$, $\eta^2 = 0.07$) and voluntary activation ($P = 0.32$, $\eta^2 = 0.14$) (Table 3). This resulted in similar MTCs ($P = 0.128$, $\eta^2 = 0.30$) and also peak torques recorded following octet stimulation were similar ($P = 0.11$, $\eta^2 = 0.32$) in the dominant (134 ± 15 Nm) and non-dominant (140 ± 9 Nm) limb. In addition, peak torques reached during the maximally fast voluntary contractions were similar ($P = 0.55$, $\eta^2 = 0.05$) in the dominant (123 ± 15 Nm) and non-dominant (130 ± 18 Nm) limb. Together the data do not indicate that the performance was better with the dominant leg.

The moderate ICCs for parameters related to voluntary isometric contractile strength (Table 3) seem to indicate that reproducibility was rather poor. However, it has to be noted that the between subject variation in maximal torque capacity during isometric knee extension effort in the present group was low (Fig. 1) and this will tend to reduce ICC. CVs for voluntary isometric contractile strength (Table 3) were acceptable (3–6%) and values obtained for maximal torque capacity during isometric knee extension effort for both legs were consistent between days and only

Table 3 Maximal voluntary isometric knee extension torque

	Dominant leg			Non-dominant leg		
		CV	ICC		CV	ICC
MVC (Nm)	217 ± 16	5.0 ± 3.9	0.72	225 ± 25	4.7 ± 5.4	0.81*
Vol activation (%)	87 ± 5	6.2 ± 4.9	0.63	89 ± 3	3.9 ± 2.5	0.62
MTC (Nm)	254 ± 14	3.2 ± 1.7	0.77*	252 ± 22	2.9 ± 3.2	0.89*

Group ($n = 8$) mean values (±SD) were based on the average values of the best attempt of each subject on each day. There were no significant differences between limbs, * denotes significant ICC

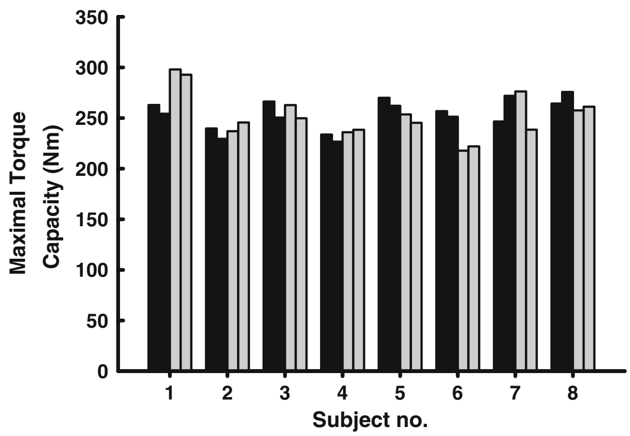

Fig. 1 For each of the eight subjects (*x*-axis) maximal isometric knee extensor torque capacity (120° knee angle) as established with superimposed stimulation upon MVC is shown for the dominant leg (*black bars*) and the non-dominant leg (*gray bars*) for the first (columns 1 and 3) and second experimental day (columns 2 and 4)

in subject no. 1 and 6 one leg may have been stronger than the other (Fig. 1).

There were no significant differences between both limbs for any of the parameters related to torque development, neither electrically induced (Table 4), nor during maximal voluntary attempts (Table 5). Voluntary MRTD was significantly lower and reached later after contraction onset (longer time to MRTD) compared to the electrically induced contractions (Tables 4, 5). Similarly, voluntary TTI40 ($P = 0.20$, $\eta^2 = 0.22$ between legs) was only 16.3 ± 7.5% (dominant limb) and 18.7 ± 10.4% (non-dominant limb) of the electrically induced TTI40, also illustrating the slower torque development during maximal voluntary attempts compared to maximally activated (electrically induced) contractions. Since fast voluntary torque onset is critically dependent on the magnitude and rate of rise in neural activation during contraction onset (Van Cutsem et al. 1998; de Ruiter et al. 2004a, b, 2007; Del Balso and Cafarelli 2007), it is not surprising that there was quite some variation among voluntary attempts within subjects; compare for example the two best attempts of subject no. 3 on both days with the dominant leg (Fig. 2). However, although the CV for voluntary TTI40 was quite high for both legs, the relative differences among the subjects were greater (compare for example subjects 6 and 7 in Fig. 2), which resulted in good ICCs for voluntary TTI40 (Table 5). In addition, when for each subject the average value of four attempts (the two best attempts on each day) was taken, there was a strong positive linear relationship ($n = 8$, $r^2 = 0.94$, $P < 0.001$) between voluntary TTI40 of the dominant and non-dominant side. Similar results were found with respect to voluntary MRTD of both limbs ($n = 8$, $r^2 = 0.84$, $P = 0.001$). Thus, although the capacity for fast voluntary torque onset clearly differed among subjects, it was very similar in both legs and for none of the subjects there was an indication for consistent differences between both limbs (Fig. 2).

There were also no indications for differences ($P = 0.82$, $\eta^2 = 0.08$) in jump performance between limbs (Fig. 3, Table 5). Similar to the parameters for voluntary

Table 4 Electrically induced (octet) isometric knee extensor contractile responses

	Dominant leg			Non-dominant leg		
		CV	ICC		CV	ICC
MRTD (Nm s^{-1})	3318 ± 579	9.1 ± 6.9	0.86*	3526 ± 667	10.4 ± 5.5	0.88*
Time to MRTD (ms)	44 ± 11	7.7 ± 7.6	0.90*	51 ± 10	8.7 ± 5.9	0.80*
TTI40 (Nm s)	0.52 ± 0.12	8.3 ± 3.9	0.96*	0.49 ± 0.08	8.5 ± 6.5	0.91*

Group ($n = 8$) mean values (±SD) based on the average values of four contractions of each subject (two on each day). There were no significant differences between limbs, * denotes significant ICC

Table 5 Voluntary fast torque development and jump height

	Dominant leg			Non-dominant leg		
		CV	ICC		CV	ICC
MRTD (Nm s^{-1})	2255 ± 740	15.4 ± 6.6	0.91*	2147 ± 578	17.7 ± 10.6	0.81*
Time to MRTD (ms)	78 ± 21	6.7 ± 3.1	0.98*	83 ± 18	11.3 ± 10.1	0.85*
TTI40 (Nm s)	0.09 ± 0.05	21.8 ± 14.8	0.96*	0.09 ± 0.05	20.9 ± 0.5	0.96*
SJ120 (cm)	21.0 ± 3.2	7.0 ± 4.2	0.93*	21.3 ± 2.6	4.9 ± 3.3	0.94*

Group ($n = 8$) mean values (±SD) based on the average values of four contractions per subject (the two best attempts on each day). There were no significant differences between limbs, * denotes significant ICC

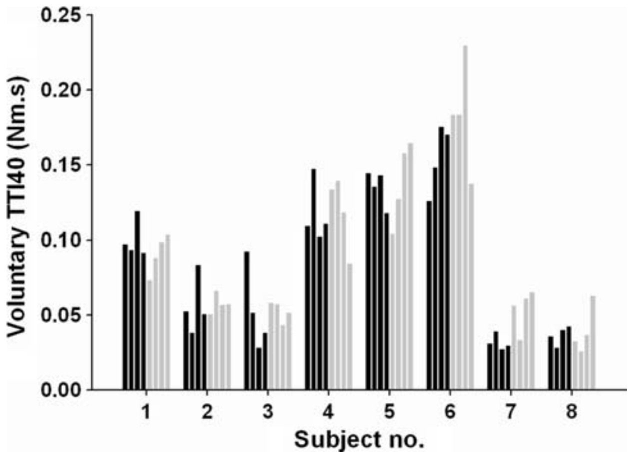

Fig. 2 For each of the eight subjects (*x*-axis) torque time integral over the initial 40 ms of maximally fast voluntary isometric knee extension (120° knee angle) is shown for the dominant leg (*black bars*) and the non-dominant leg (*gray bars*). For each subject the best two attempts for the first (columns 1–2 and 5–6) and second experimental day (columns 3–4 and 7–8) are shown

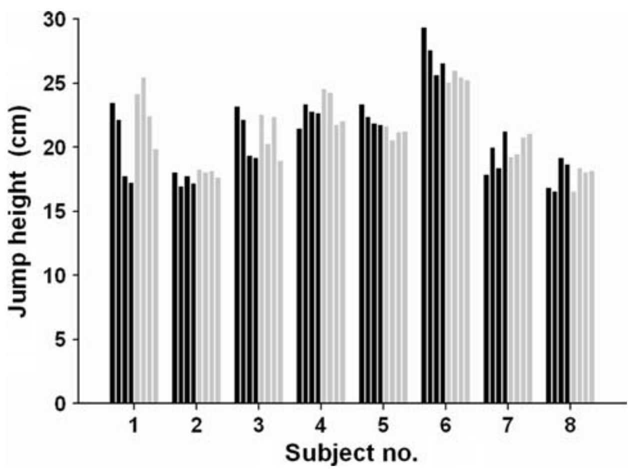

Fig. 3 For each of the eight subjects (*x*-axis) squat jump height starting from a 120° knee angle is shown for the dominant leg (*black bars*) and the non-dominant leg (*gray bars*). For each subject the best two attempts for the first (columns 1–2 and 5–6) and second experimental day (columns 3–4 and 7–8) are shown. Note that the investigators (blind to the results of the first test day) wrote in the lab journal that subject no. 1 'showed a lack of motivation during the jump tests' on the second test day

torque development, there was a significant positive relation for jump performance (average values of four: the best two attempts on each day) between legs ($n = 8$, $r^2 = 0.88$, $P = 0.001$). In addition, the capacity for fast voluntary torque onset in the dynamometer (TTI40) was significantly related to jump performance both for the dominant limb ($n = 8$, $r^2 = 0.75$, $P = 0.005$) and the non-dominant limb ($n = 8$, $r^2 = 0.69$, $P = 0.011$). There were no significant relations ($r^2 < 0.13$) between any of the parameters obtained with electrical stimulation and jump height.

Discussion

The primary findings of the present study were that, neither during electrical stimulation nor during voluntary effort the knee extensor muscles of the dominant limb were stronger or faster than those of the non-dominant limb. In addition, unilateral squat jump performance, involving the coordinated activity of more muscle groups than the knee extensors, did not differ systematically between the dominant and non-dominant leg.

The present results are in line with several previous findings involving other unilateral lower limb tasks such as static balance control (Hoffman et al. 1998; Lin et al. 2009) and unilateral squatting exercise (McCurdy and Langford 2005). In addition, in female soccer players jump performance was also found to be similar in legs (Ostenberg et al. 1998). Moreover, during isometric (Hotta et al. 2007) and isokinetic knee extension dynamometry (Mognoni et al. 1994; Ostenberg et al. 1998; Zakas 2006) systematic differences in performance were not reported, although in the study of Hotta et al., subjects performed better with their dominant (kicking) limb during isokinetic knee extensions (Hotta et al. 2007). The present findings confirm and expand the majority of earlier observations by demonstrating that both the isometric strength of the knee extensor muscle–tendon complex itself as well as the subjects ability to voluntary activate the muscles did not differ between the dominant and non-dominant limb. The similar voluntary muscle activation at the torque plateau of isometric knee extensions has been found before (Guette et al. 2005), but a new finding of the present study was that maximally fast isometric knee extensor torque development, both electrically induced and voluntarily elicited, were also similar in the dominant and non-dominant limb.

Different studies have used different tests for leg dominancy and perhaps the test of choice affected the results. Therefore, in the present study three of the most often applied tests were used. The outcome was very consistent among the tests. The balance recovery and the step up test were performed three times and only subject no. 7 on one occasion used his other leg to step up. Table 2 shows that, using the standard tests, subjects 1 and 8 were clearly left-legged while the other subjects had a dominant right leg. Despite the consistent outcomes of the dominancy tests, performance with the dominant leg was not superior during maximal (fast) isometric knee extensions and jumping.

In the present study knee flexor function was not investigated, primarily because the knee flexors cannot be selectively and maximally activated with electrical stimulation. In previous studies antagonist muscle activity during maximally fast isometric contractions (co contraction) was found to be negligible (de Ruiter et al. 2004a, b, 2006, 2007). Moreover, the similar voluntary extension MVCs between dominant and non-dominant leg do not indicate that side-dependent differences in knee flexor co contraction were present. In addition, consistent differences in knee flexors strength were probably not present, since during squat jumping the knee flexors contribute substantially to work done during push off (Bobbert and Casius 2005), but jump performance was very similar in both limbs.

Isometric rather than isokinetic contractions were studied because maximal electrically induced isometric torque development clearly defines the maximal capacity for torque development of the muscle tendon complex, which subsequently can directly and easily, be compared with voluntary fast torque development (de Ruiter et al. 2004a, b, 2007). Note that during isometric torque development the contractile elements of muscle fibers actually shorten while the series elastic components are stretched. Thus fast 'isometric' torque development actually is a dynamic action for the contractile components of the muscle. In addition, as pointed out before (Aagaard et al. 2002a, b) torque time integral (over 40 ms in the present study; TTI40) during the early phase of torque development is equivalent to the impulse (moment of inertia times rotational limb velocity) of a freely extending leg. TTI40 has previously been shown to significantly depend ($0.66 < r^2 < 0.75$) on the subjects' ability for fast rate of rise in neural activation at the start of a contraction (de Ruiter et al. 2004a, b, 2006, 2007). Moreover, it was demonstrated that unilateral isometric torque development (TTI40) was significantly related to *bi*lateral jump performance (de Ruiter et al. 2006). Therefore, it was not surprising that in the present study unilateral TTI40 was significantly related to *uni*lateral jump performance. Voluntary TTI40 was only 16–19% of the electrically induced TTI40, a value comparable to previous findings (de Ruiter et al. 2004a, b, 2007). Note that, because the emphasis of the instruction was to produce a fast contraction, peak torques reached during the maximally fast voluntary contractions, were about 58% of the plateau torques obtained during MVCs. In our experience maximal voluntary rates of torque rise cannot be obtained when subjects also try to generate peak torques similar to MVC values in the same contractions. Thus, during the first 40 ms of maximal voluntary torque development on average only 16–19% of the knee extensor muscles' capacity for torque development was used during voluntary effort. An important finding was that for each subject the ability for voluntary fast isometric torque development (Fig. 2) and jump performance (Fig. 3) were similar in both limbs. Fast ballistic type of actions, such as the early phase of isometric torque development and squat jumping are preprogrammed. In terms of neural activation performance is probably dominated by the central drive from the cortex to the motoneurons, although peripheral factors (motoneuron excitability and presynaptic inhibition) may also determine output during fast torque development (Aagaard et al. 2002a, b). Training has shown to enhance neural activation and thereby fast torque development (e.g., Aagaard et al. 2002a, b; Del Balso and Cafarelli 2007).

In the present study, training background differed among the subjects, but none of the subjects was involved in exercises clearly loading/training one leg more than the other (Table 1). In tennis players bone mineral density and grip force were greater in the playing arm compared to the other arm (Ducher et al. 2005). In soccer players knee flexors (but not extensors) were found to be weaker in the dominant (preferred kicking) leg versus the non-preferred side (Rahnama et al. 2005) and isokinetic strength was reported to be higher for hip flexors and lower for the knee extensors in the kicking (dominant) leg (Mognoni et al. 1994). These studies on trained soccer players suggest that selective training of legs could lead to side specific adaptations in muscle strength and architecture (Kearns et al. 2001). However, Zakas et al. also studied professional soccer players and in their study dynamic knee extensor strength was similar in both legs (Zakas 2006).

Under certain conditions, like during long-term unilateral (un)loading, differences in neural activation and muscle fiber properties will occur between limbs but usually such differences are unlikely to be present. For example, maximal rates of voluntary isometric knee extensor torque development and MVC were similar in the take off and the contralateral leg in track and field athletes (Sahaly et al. 2001).

It is important to emphasize that the present study does not want to question (the importance of) the concept of limb dominancy in general. Studies using fMRI have clearly shown that lateralization of brain activity exist and may be affected by several factors including limb dominancy (e.g., Kapreli et al. 2006). Although finger movements had stronger lateralized brain activation patterns than lower limb movements, also during the latter there were dissimilarities in brain activity between the dominant and non-dominant limb during low force movements (Kapreli et al. 2006). Nevertheless, the current results provide further evidence that for standard maximal dynamometry testing lower limb dominancy, determined using standard tests or by asking for the subjects' preferred kicking leg, may not be important. It remains to be investigated if for instance movement accuracy or muscle fatigue will also be similar in the dominant and non-dominant leg and we cannot exclude that results for closed chain testing (leg press) or for concentric and eccentric contractions may differ from the present findings obtained during single joint isometric contractions and squat jumping.

Nevertheless, based on the literature and the present results the dominant leg would probably be best defined as the leg with which performance is best during the task at hand (van der Harst et al. 2007) and in general it may be better to use the terms 'preferred' and 'non-preferred' (Rahnama et al. 2005) in relation to lower limb function.

The practical implication of the current (and many previous) findings is that during lower limb dynamometry testing in rehabilitation, the contralateral limb can be used as a valid control limb, regardless whether this would be the dominant or the non-dominant limb. Similarly, in studies involving athletes, who during testing often have minor injuries in one of their legs (e.g., patello femoral pain), the contralateral leg, regardless whether this would be the 'dominant' or 'non-dominant' leg, can usually be tested without significant effects on the study outcome.

In conclusion, fast unilateral knee extensor torque generating capacity, neural activation, and squat jump performance were very similar in the 'dominant' and 'non-dominant' limb in healthy not specifically trained subjects. The magnitude of neuromuscular activity at the onset of fast isometric contractions differed substantially among subjects, with strong correlations between fast voluntary isometric torque development and jump height, but without differences between the limbs. These findings further challenge the concept of lower limb dominancy in dynamometry testing in sports and rehabilitation.

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