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Impact of sensorimotor training on the rate of force development and neural activation

Abstract The ability to generate high muscular strength within short time periods is of functional importance not only as a basic quality in many sports disciplines but also for active stabilization of joints. The rate of force development (RFD) is generally used to describe this ability. The purpose of the present study was to examine the functional adaptations of a specific sensorimotor training on the explosive strength qualities of the leg extensor muscles during maximum isometric actions. Force and surface EMG were recorded in 17 subjects before and after a 4-week sensorimotor training period. Maximum static leg press strength did not change [608.2 (47.0) N to 627.8 (48.4) N before/after training], whereas maximum RFD (RFD_{max}) increased significantly from 4.95 (0.48) N/ms to 6.58 (0.76) N/ms ($P < 0.05$). The gain in RFD_{max} was accompanied by an increased EMG of the M. vastus medialis. Enhancement of neuromuscular activation was only prominent in the early phases of muscular action. Neither force nor EMG parameters revealed significant improvements for time phases beyond 100 ms following the onset of isometric action. Enhanced extrafacilitatory drive from the afferent system is discussed as a potential mechanism for the improved neural activation. From a more functional point of view, this type of adaptation may be helpful in various sport performances. Moreover, with regard to injury related situations, enhanced neuromuscular activation is of distinct relevance in order to stiffen joint complexes actively within short time periods.

Keywords Sensorimotor training · Rate of force development · Neuromuscular adaptation

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Introduction

The rate of force development (RFD), generally determined as the slope in the force time curve ($\Delta force/\Delta time$), is important to assess the explosive strength qualities of the neuromuscular system (Schmidtbleicher and Haralambie 1981; Hakkinen and Komi 1983, 1986; Hakkinen et al. 1985, 1998; Aagaard et al. 2002a). High RFD is functionally a prerequisite to attain relevant impulses, especially in fast limb movements or sport disciplines with a limited time of muscular action. Recently there has been growing interest in the literature about the functional importance of quick neuromuscular activation in injury-related situations in order to stiffen joint complexes (Konradsen et al. 1998; Alt et al. 1999; Bloem et al. 2000).

It is well documented that improvements in force production capacity can be achieved either by enhancement of the muscular protein mass (MacDougall et al. 1980; Staron et al. 1990, 1991; Narici et al. 1996), or by adaptations in the neural control of the muscle (Moritani 1993; Narici et al. 1996; Aagaard et al. 2002a). While maximum voluntary strength largely depends on the cross sectional area of the muscle, RFD is basically related to the discharge rate of the motor units recruited (Nelson 1996; Van Cutsem et al. 1998), to alterations in the recruitment characteristics (Kukulka and Clamann 1981) or to a combination of both (Duchateau and Hainaut 2003).

It has been shown that an increase in force development is closely related to improvements in neural drive of the trained muscles, especially in a dynamic, explosive type of strength training (Hakkinen et al. 1985). More recently, Van Cutsem et al. (1998) have proved that neural adaptations caused by an explosive type of training are primarily responsible for an increased RFD. By analyzing single motor unit recordings the authors were able to demonstrate the preservation of the orderly motor unit recruitment pattern. However, after training, motor units were activated earlier and showed increased firing frequencies. From intramuscular EMG

recordings the authors support the idea that explosive type of training is associated with high frequency discharges ("doublets") occurring at the onset of muscular action.

Numerous studies have reported that the actual efferent motor contribution is determined not only by centrally generated, but also by peripherally generated activation processes. It has been suggested that proprioceptive enhancement of neural activation may have a positive influence on the actual excitation of the motoneuron system, especially for the stretch-shortening-cycle (Komi 1984; Gollhofer et al. 1987, 1992).

From a practical point of view, sensorimotor training is well established in the prevention and rehabilitation of ankle and knee joint injuries (Caraffa et al. 1996; Sheth et al. 1997; Rozzi et al. 1999). It is assumed that this type of exercise is highly efficient for attaining increased proprioceptive input to the neuromuscular system or for processing information of the proprioceptive system more appropriately.

The purpose of this study was to test the hypothesis that a specifically designed sensorimotor training will produce an increase in neural activation and explosive strength at the beginning of a maximal static leg press exercise.

Methods

Subjects

Seventeen subjects [12 female subjects, ages 27.8 (6.5) (SD) years, height 1.67 (0.04) m and body mass 63.2 (3.1) kg] and five male subjects, ages 31.4 (5.8) years, height 1.76 (0.08) m and body mass 71.8 (5.2) kg] participated in the study. The experimental procedures were explained and all the subjects gave their informed consent. The subjects were healthy with no history of serious lower extremity (specifically ankle or knee joint) injury. None of the subjects had previously participated in systematic sensorimotor training. Local ethical permission was given and all experiments were conducted according to the Declaration of Helsinki.

Training program

The subjects carried out a specifically designed sensorimotor training program over a period of 4 weeks, with a total of eight training sessions. All sessions were documented, surveyed and supervised by the authors of this study. The subjects trained twice a week with at least 1 day rest between the training sessions. Each training session lasted for 60 min and started with a 10 min warm-up program on a bicycle dynamometer at 100 W. The postural stabilization tasks consisted of exercises on wobbling boards, spinning tops, soft mats (Airex, Aalen, Germany) and on two-dimensional free moving platforms (Posturomed, Pullenreuth, Germany). Each type of exercise had to be performed unilaterally with eyes opened and with hands akimbo. Each stabilization task was carried out four times for 20 s with 20 s rest between the sets. The rest period between the exercises was 5 min. Each stabilization task was performed with the objective to retain balance. In order to focus primary adaptations to the muscles encompassing the knee joint, all subjects had to wear ski boots throughout the training session. This ensured that most of the postural stabilization tasks were performed by the

quadriceps and the hamstring muscles. The training session ended with a 10-min cool-down program on a bicycle dynamometer at 100 W. This training regimen has been described in detail by Gruber (2001).

Protocol

Maximum leg press strength was measured on a specially designed leg press (Phoenix, Stuttgart, Germany) equipped with a force platform (Kistler, Winterthur, Switzerland). The subjects were positioned on the sledge of the leg press with the hip, knee and ankle angles adjusted at 90°. The waist was fixed and the subjects were allowed to stabilize their upper body by holding on to handles attached to the leg press. The position of each subject was documented so that it was identical under the pre- and post- conditions. Testing was only performed on the right leg. A warm-up period of 5–10 min followed by three to five submaximal isometric actions in the leg press was allowed for each subject to become accustomed to the testing procedure. Thereafter, each subject performed three to four leg press exercises with maximal voluntary effort. For each trial, subjects were thoroughly instructed to act "as forcefully and as fast as possible".

The force signal perpendicular to the footplate and the EMG signals were synchronously sampled at 500 Hz. The raw unfiltered signals were analog-to-digital converted (DAQ700, National Instruments, USA) and stored on a PC. During later offline analysis the trial with maximum static leg press strength was selected and the force signal was filtered by a digital fourth order recursive Butterworth low-pass filter, using a cutoff frequency of 50 Hz. Onset of force was determined at 2% of each individual's maximum force value. In Fig. 1A an individual example is depicted to show force and EMG records of the maximal isometric action. Another example (Fig. 1B) shows the initial 300 ms of the pre- and post- comparison and the rectified summed electromyography (EMG) of the vastus medialis (VM) and the vastus lateralis (VL), respectively.

The following parameters were analyzed: Maximum isometric force (F_{max}) and RFD were calculated from the individual maximal isometric force development record (Fig. 1B). RFD_{max} was defined as the maximal slope of the force time curve ($\Delta force/\Delta time$) (Schmidtbleicher and Haralambie 1981). Time to reach RFD_{max} was determined as the time to reaching RFD_{max} relative to the onset of force. Additionally, submaximal RFD-values were calculated as mean slope of the force-time curve (d F/d t) over time intervals of 0–30, 0–50, 0–100 and 100–200 ms relative to the onset of force (Hakkinen and Komi 1983, 1986; Hakkinen et al. 1985; Aagaard et al. 2002a). Force values were determined at 30, 50, 100, 200, 300, 400 and 500 ms relative to the onset of force. Normalized force values were determined as force relative to maximum force (expressed as %F_{max}).

Electromyography

Bipolar surface electrodes (Hellige, Germany) (diameter 10 mm, center to center distance 25 mm) were placed over the VM, the VL, the biceps femoris (BF) and the semitendinosus (ST) of the right leg. The longitudinal axes of the electrodes were in line with the presumed direction of the underlying muscle fibers. All electrode positions were carefully determined and marked to ensure identical pre- and post-training recording sites. Interelectrode resistance was kept below 5 kΩ by means of shaving, light abrasion, degreasing and disinfecting the skin. EMG electrodes were directly connected to custom built differential pre-amplifiers (gain 200, input impedance 4,000 MΩ, common mode rejection 75 dB at 60 Hz) and taped to the skin. The pre-amplified signals were led through shielded cables to the main amplifier [band-pass filter 10 Hz–1 kHz, gain 6.25 (resulting in an overall gain of 1,250)].

Mean rectified EMG amplitudes [mean average voltage (MAV)] were determined for the distinct time intervals 0–30, 0–50, 0–100,
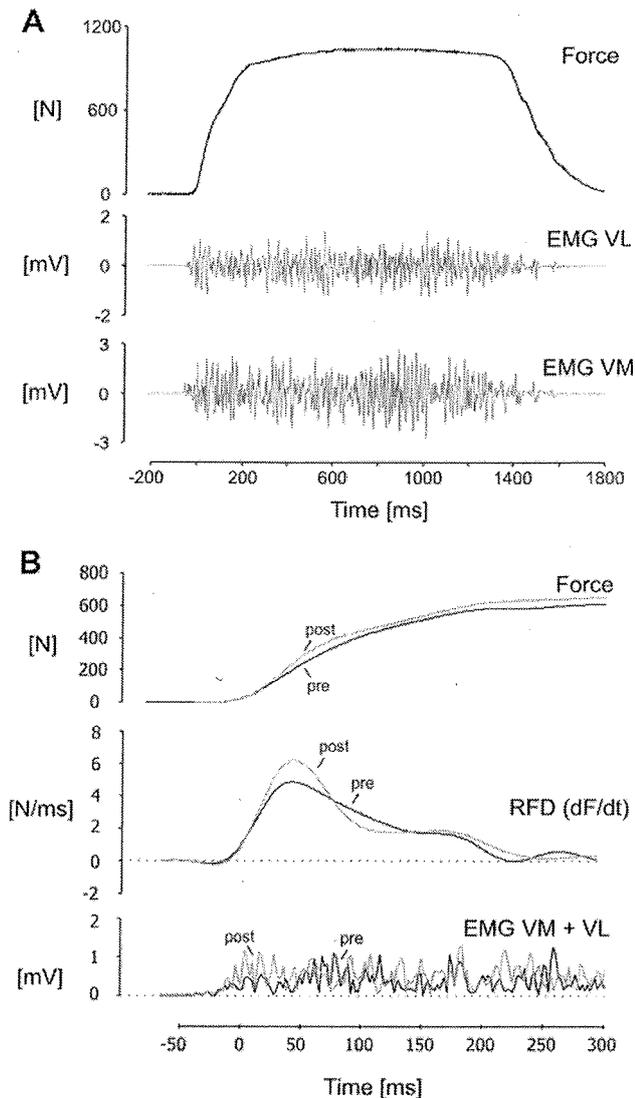
Fig. 1 A Force and raw EMG signals of one subject recorded during a trial of maximal isometric action of the quadriceps femoris muscle in the leg press. *VL* Vastus lateralis; *VM* vastus medialis. Time 0 corresponds to the onset of the force curve. **B** Force, RFD and rectified EMG signals before and after the training (pre: *black line*, post: *grey line*), a different subject than in **A**. Note the change in axis range. RFD was calculated as the slope of the force time curve (d F/d t). Quadriceps EMG was calculated as the sum EMG of VM and VL

100–200, 200–300, 300–400 and 400–500 ms relative to the onset of force and 50 ms before and after F_{max} (MAV$_{Fmax}$). Normalized MAV values were determined as MAV relative to MAV$_{Fmax}$ (expressed as % MAV$_{Fmax}$).

Reliability

Test-retest reliability was determined by a separate analysis of 21 subjects. Maximal isometric actions were performed on the identical apparatus. Retest reliability was determined for all parameters of the present study by the Pearson product-moment method using linear regression analysis. The time period between the first and the
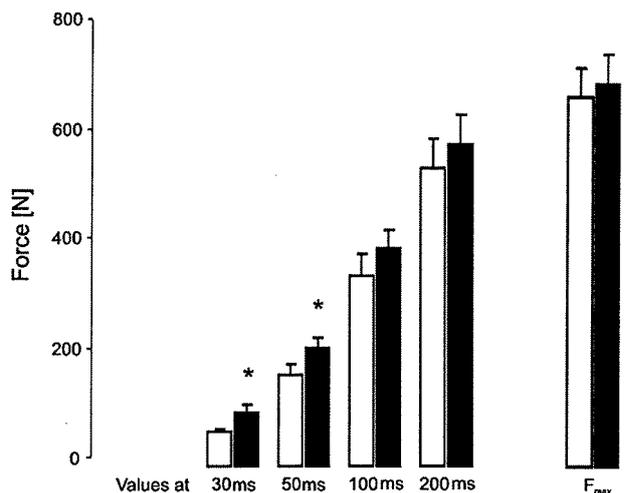
Fig. 2 Force [means (SE)] at 30, 50, 100 and 200 ms after the onset of force before (*open bars*) and after (*filled bars*) the sensorimotor training. In addition F_{max} was determined from the force time curve (d F/d t) before (*open bar*) and after (*filled bar*) the training. Pre- to post-training differences: *$P < 0.05$

second measurement was set to 28 days in order to fit the pre-set longitudinal protocol. Within this period subjects were not allowed to practice a sensorimotor program. The reliability of force, RFD and impulse parameters proved to be between $r_{tt} = 0.68$ and 0.96. The respective coefficients for the MAV values were slightly lower for the flexor than for the extensor muscles. Values ranged between $r_{tt} = 0.42$ and 0.82 for the flexor and $r_{tt} = 0.58$ and 0.91 for the extensor muscles.

Statistical analysis

Data are presented as group mean values (SE). Pre- to post-training changes were analyzed using Student's t-test for paired samples (two-tailed, 0.05 level of significance).

Results

Maximum static leg press strength (F_{max}) remained unchanged [608.2 (47.0) N before and 627.8 (48.4) N after training], whereas the absolute force values increased at 30 ($P = 0.011$) and 50 ms ($P = 0.036$) relative to the onset of force development. The respective values at 100 ms ($P = 0.082$) showed a trend towards an increase. No adaptations could be observed for force values at 200 ms (Fig. 2).

Maximum RFD increased from 4.95 (0.48) N/ms to 6.58 (0.76) N/ms ($P = 0.021$) whereas time to reach RFDmax remained unchanged [56 (3) ms before training and 52 (4) ms relative to the onset of force after training]. After training mean RFD values increased in the time intervals 0–30 ($P = 0.009$) and 0–50 ms ($P = 0.034$). In the time interval 0–100 ms a trend towards a change could be observed ($P = 0.089$), whereas no changes could be found during the time interval 100–200 ms (Fig. 3).
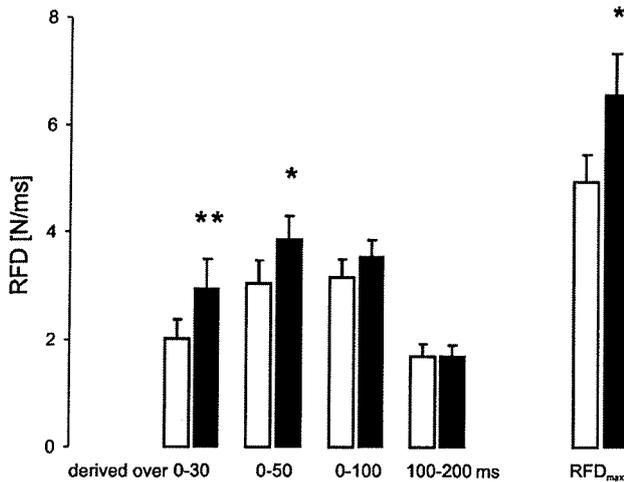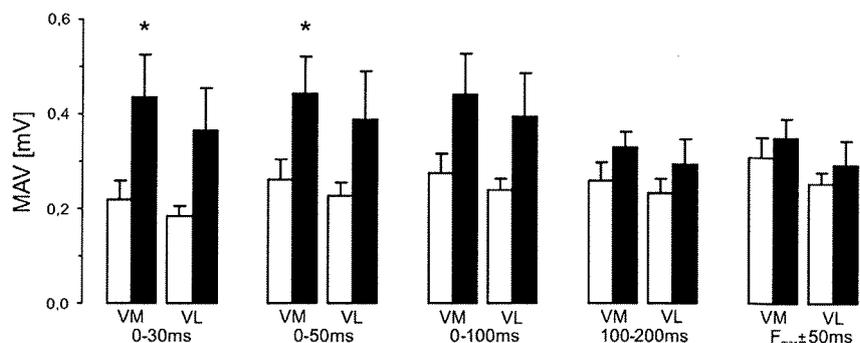
Fig. 3 RFD [means (SE)] in time intervals of 0–30, 0–50, 0–100 and 100–200 ms relative to the onset of force development before (*open bars*) and after (*filled bars*) the sensorimotor training. In addition RFD_{max} was determined from the force time curve (d F/d t) before (*open bar*) and after (*filled bar*) the training. Pre- to post-training differences: $**P < 0.01$ and $*P < 0.05$

Discussion

Sensorimotor training had a great impact on the neuromuscular system at the initiation of force production. We were able to demonstrate that this type of training seems to be highly efficient for enhancing explosive strength and neuromuscular activation at the onset of voluntary actions.

Significant adaptations could only be found in the early time intervals after the onset of force development. This phase dependency was reinforced by the fact that in the early time phases of 0–30 and 0–50 ms even relative force values were enhanced (Fig. 5).

In classical strength training studies with a heavy resistance or an explosive type of strength training (Schmidtbleicher and Haralambie 1981; Hakkinen and Komi 1983, 1986; Hakkinen et al. 1985, 1998; Van Cutsem et al. 1998; Aagaard et al. 2002a) increases in strength are reported to be associated with increased neural drive over the entire duration of muscular action. However, selective adaptations of RFD and maximum force capacity have been reported for specific training regimens. For instance, Hakkinen (Hakkinen and Komi 1986) has shown that resistance training primarily leads to an enhanced maximum force whereas explosive type of training results in adaptations basically related to the RFD.

In accordance with these classical training studies we found similar effects: sensorimotor training increased the RFD without enhancing maximum strength. In line with the study presented by Aagaard et al. (2002a) we found concurrent increases in the RFD and the MAV in the earliest time phases of muscular action (0–30 and 0–50 ms after the onset of EMG integration for VM). However, it has to be remarked that Aagaard et al. examined single joint movements whereas in our study a complex multi-joint movement was investigated. Therefore, for the present study, an interpretation of a possible modulation of the force/EMG relationship due to sensorimotor training can be given only indirectly on a single muscle level. Altered MAV and RFD without enhancements in maximum strength could also be explained by alterations in the relative onset of activation of the various muscles encountered in the force pro-

Following training, the absolute MAV of the VM were enhanced in the time intervals 0–30 ($P = 0.011$) and 0–50 ms ($P = 0.035$) for VM. Trends towards a change could be observed for the VM in the time interval 0–100 ms ($P = 0.085$) and for VL in the time intervals 0–30 ($P = 0.067$), 0–50 ($P = 0.096$) and 0–100 ms ($P = 0.091$). No changes in the EMG amplitude could be found for the time interval 100–200 ms and for the time interval 50 ms pre- and post- F_{max} (Fig. 4).

Normalized force values (%F_{max}) increased significantly at 30 ($P = 0.002$) and 50 ms ($P = 0.024$). No changes could be observed with regard to force values beyond 100 ms after the onset of force development (Fig. 5). During the early phase of muscular action the normalized MAV increased drastically for VM 97% (0–30 ms) and 70% (0–50 ms) and for VL 99% (0–30 ms) and 70% (0–50 ms). For time intervals beyond 0–100 ms neither changes nor trends towards a change could be found (Fig. 5). The antagonist hamstring EMG remained unchanged.

Fig. 4 MAV [means (SE)] of the vastus medialis (*VM*) and vastus lateralis (*VL*) in time intervals of 0–30, 0–50, 0–100 and 100–200 ms relative to onset of force development as well as 50 ms pre- and post-F_{max} [F_{max} (50 ms)] before (*open bars*) and after (*filled bars*) the sensorimotor training. $*P < 0.05$

Fig. 5 Normalized force time curve averaged for all subjects before (*black line*) and after (*grey line*) sensorimotor training. Normalized force values 30, 50, 100, 200, 300, 400 and 500 ms after the onset of force before (*open diamonds*) and after (*filled triangles*) sensorimotor training as well as normalized MAV in time intervals of 0–30, 0–50, 0–100, 100–200, 200–300, 300–400 and 400–500 ms of the leg extensor muscles (VM + VL) averaged for all subjects before (*open squares*) and after (*filled circles*) sensorimotor training. Pre- to post-training differences: $**P < 0.01$ and $*P < 0.05$
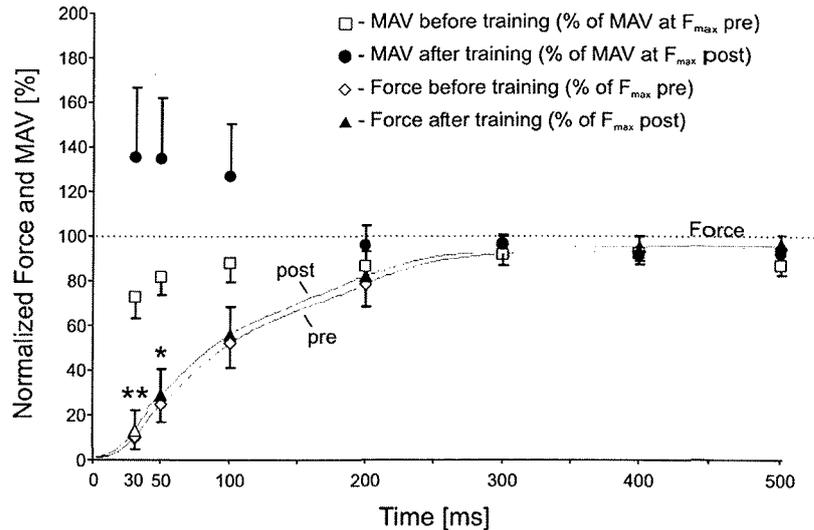
duction of a leg press exercise. However, our data did not support this hypothesis. Moreover, the present methodological approach does not provide a holistic picture from all muscles contributing to the isometric contraction and there exists a hypothetical possibility that muscles other than those examined are also modulated after training. However, due to the well-controlled and highly reliable condition of the pure isometric strength tests, possible divergent influences from other muscles may be minimal and thus not effective enough to play a major role in a before/after training comparison. Therefore, the simplest interpretation concentrates primarily on the effects occurring at a single muscle level.

Increased strength and neural activation require adaptations on the motoneuron level, i.e., motoneuron recruitment and/or firing frequency, alterations in synchronization of motor unit firing and/or even advanced incidences of discharge doublets as proposed by Duchateau and Hainaut (2003).

The functional background between higher motoneuron firing frequencies on the one hand and higher RFD on the other has been discussed in detail by Aagaard et al. (2002a). Frequency/force relationships have been shown for isolated muscle fibers (Metzger and Moss 1990a, 1990b), for the entire muscle in situ (Buller and Lewis 1965) as well as for human skeletal muscle in vivo (Grimby et al. 1981; Nelson 1996). Increases in RFD can be achieved either by higher firing frequencies or by extra impulses (Burke et al. 1970) even though the firing frequency for maximum tetanic tension has already been reached (Desmedt and Godaux 1977; Miller et al. 1981; Nelson 1996). Recently, Van Cutsem et al. (1998) reported that a ballistic type of resistance training led to an increase in RFD along with an elevated incidence of discharge doublets (interspike intervals 2–5 ms) in the firing pattern of motor units. They interpreted that the functional significance of these extra doublets is basically to enhance maximal tension development.

Thus, the presented increases in neural drive during the initial phase of force development may reflect an increase in motoneuron firing frequency in response to sensorimotor training.

It has to be mentioned that gains in neural drive may also be related to an alteration of the recruitment threshold of motoneurons (Henneman et al. 1965). Some results have been presented by Grabiner et al. (1994) who investigated maximal knee extensor muscle actions in association with antagonist conditioning actions.

Based on single motor unit recordings, motor unit synchronization has been considered a potential mechanism to modulate force development (Milner-Brown et al. 1975; Semmler and Nordstrom 1998). Semmler drew the conclusion that most likely the functional role of synchronization is to increase RFD, especially in situations where different muscles have to be coordinated (Semmler 2002).

Overall, increased frequency, earlier recruitment as well as improved synchronization can be understood as an excitatory modulation of the spinal motoneuron pool. Several authors assume that following strength training main adaptations occur in supraspinal structures caused by an enhanced neural drive in descending corticospinal pathways as indicated by higher V-wave amplitudes (Sale et al. 1983; Aagaard et al. 2002b). However, due to methodological reasons a reduction in presynaptic inhibition of Ia afferents can not be excluded.

Is there a chance for adaptations in spinal contributions caused by sensorimotor training? From walking (Sinkjaer et al. 2000) as well as from voluntary ramp actions (Meunier and Pierrot-Deseilligny 1989; Macefield et al. 1993) it is known that proprioceptive afferent feedback influences muscular action to some extent. Meunier and Pierrot-Deseilligny (1989) produced some evidence that both homonymous and heteronymous Ia contributions are facilitated at the beginning of muscular action.

On the one hand the excitability of the spinal reflex system is clearly linked to the requirements given by the functional tasks, i.e., sitting, standing, walking (Capaday and Stein 1987; Edamura et al. 1991; Hayashi et al. 1992; Simonsen and Dyhre-Poulsen 1999). On the other hand it is supposed that a specific training regimen could influence spinal excitability, which has been shown for alternatively trained athletes (Rochcongar et al. 1979; Casabona et al. 1990; Nielsen et al. 1993; Maffiuletti et al. 2001) as well as after a training intervention (Voigt et al. 1998). Furthermore, functional adaptations of the spinal reflex system have been described while balancing (Llewellyn et al. 1990; Hayashi et al. 1992; Trimble and Koceja 2001) for balance trained athletes (Nielsen et al. 1993) and after balance training (Trimble and Koceja 1994; Gruber et al. 2000). Recently, Gollhofer and Gruber have reported functional improvements following a sensorimotor training (Gollhofer 2003; Gruber et al. 2000). They argued that training on unstable platforms or surfaces elicits an intense reflex activation. Given the assumption that adaptations seen in the present study are peripheral and basically mediated at the spinal level, it can be argued that these reflex contributions could even activate the muscle during the onset of an isometric action (Hultborn et al. 1987; Macefield et al. 1993; Garland and Miles 1997).

Enhanced afferent gain in neuromuscular control, especially at the onset of force development, is of vital functional importance for the stiffening of muscles encompassing joint complexes. For ramp and hold voluntary contractions, Meunier and Pierrot-Deseilligny (1989) showed that motoneuron excitability is directly related to the target strength. This facilitation, however, depends on the steepness of the ramp and thus at least indirectly on the rate of force development as well as on the intensity of the target action. This modulation that has been mainly attributed to reduced presynaptic inhibition of Ia afferents (Meunier and Pierrot-Deseilligny 1989). Functionally, increased reflex gains are important to meet appropriate loading during muscular action.

The gains in neural drive may comprise both supraspinal and spinal adaptations. From the data of the present study, it is suggested that sensorimotor training has a great impact on proprioceptive afferent contributions, i.e., peripheral presynaptic inhibition of Ia terminals on motoneurons of the acting muscle (for a review see Vallbo et al. 1979). In contrast to specific adaptations following heavy resistance training (Hakkinen and Komi 1983; Hakkinen et al. 1985, 1998; Aagaard et al. 2002a) and ballistic training (Van Cutsem et al. 1998), the increase in RFD after a sensorimotor training regimen was not associated by an increase in maximum strength. Indeed, it seems as if main adaptations took place at the very beginning of muscular action due to the fact that both mechanical variables as well as the MAV revealed increases in the time interval 0–30 ms after the onset of force development. Moreover force values
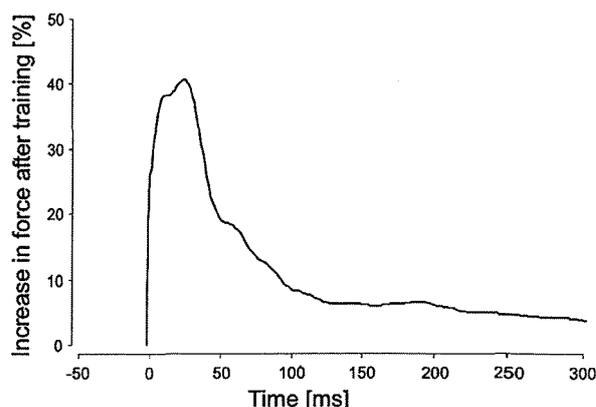

Fig. 6 Percentage increase in force over time after the training (mean values, $n = 17$). Steeper slopes of the force time curve were observed in the very early phase of force development (0–100 ms) resulting in increases in force values, RFD and impulse in this phase of muscular action

increased up to 40% in the first 30 ms after the onset of force (Fig. 6).

The present study clarifies the impact of a moderate sensorimotor training on neuromuscular adaptation. It has been demonstrated that sensorimotor training primarily enhances the strength capacity at the onset of an isometric action. This is characterized by an increased rate of force development in line with an enhanced early neural activation of the VM. It is therefore assumed that this type of training is selectively beneficial for the explosive type of muscular actions. The gain in neuromuscular activation may arise from enhanced reflex contributions acting on a spinal level, induced by the training itself. Due to the specific demands of a sensorimotor training, it can be speculated that withdrawal of presynaptic inhibition of Ia terminals, belonging to the motoneurons of the acting muscle, is most likely to explain our findings.

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