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Original Research

Muscle activation patterns in cross country skiers with a history of anterior compartment pain

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Abstract

A large proportion of elite cross country skiers (X/C-skiers) suffer from chronic anterior compartment syndrome (CACS). This cross-sectional study used surface electromyograms (EMGs) to investigate if differences exist in the activation characteristics of the *tibialis anterior* muscle between elite X/C-skiers with a history of anterior compartment pain (symptomatic group) and a pain-free control group.

Based on self-reported pain symptoms twelve young, national-level cross country ski athletes were assigned to a symptomatic group (N=5), a control group (N=4), or analyzed individually if their diagnosis was not certain (N=3). EMGs were recorded on five muscles of the lower leg. The *relative increase of EMG power per step* when increasing the effort level of skating and *EMG power spectra* were compared between groups.

Large effect sizes were found in the *increase of EMG power per step* of the tibialis anterior, peroneus longus, and gastrocnemius lateralis. The *EMG power spectra* showed significant differences in the tibialis anterior but not in other muscles. Within the step cycle, these differences appeared in the swing phase and in a gliding phase during single leg support. The observed differences in the EMG spectra might serve as an early identification of subjects who are at risk of developing CACS.

(200 words)

Introduction

Cross-country skate skiing is a low impact but physically demanding activity enjoyed by the general public, as well as by ski racers and biathletes in highly competitive settings. Injury rates in cross-country skiing are low (Butcher and Brannen, 1998), however, about 75% of the injuries that occur are chronic (Renstrom and Johnson, 1989). Chronic anterior compartment syndrome (CACS) is one of the most common causes of chronic pain in cross-country skiers (Clanton and Solcher, 1994; Gertsch et al., 1987; Lawson et al., 1992; Styf, 1988). CACS is considered to be an overuse injury of the muscles in the anterior compartment of the lower leg. It is characterized by an increase of intracompartmental pressure during and after exercise (Styf and Korner, 1986), leading to pain, swelling, and impairment of muscle function. Other symptoms include tightness of the muscle compartment, severe muscle cramping and in serious cases paresthesia. The typical treatment of CACS in elite athletes is a surgical relief of the compartment pressure by fasciotomy (Allen and Barnes, 1986; Rorabeck et al., 1983; Styf and Korner, 1986; Wallenstein, 1983).

Neither the causes of CACS nor the effects of CACS on the athlete and on athletic performance have been studied in depth. Potential risk factors for developing CACS may be found in the subject specific anatomy and particularly in the capillary density (Edmundsson et al., 2010). However, it is not known what triggers the onset of CACS or what factors may aggravate the symptoms. The investigation of physiological changes that coincide with CACS symptoms may therefore help to develop a better understanding of this condition.

In cross country skiing, CACS develops predominantly in athletes who practice daily at high intensity. Changes in the muscle activation characteristics might therefore be a contributing factor in the development or aggravation of CACS in these athletes. Overuse of the muscles may lead to structural changes in the muscles. This in turn may lead to abnormal increases of the intracompartmental pressure during exercise. Conversely, increased compartment pressure has been shown to affect the intensity of the EMG signal Maton et al., 2006; Korhonen et al., 2005) and to correlate negatively with the EMG mean power frequency (Crenshaw et al., 1997). It has been suggested that a disproportionate increase of the EMG intensity when the effort level of an exercise is increased may be a risk factor for overuse injuries (Chang et al., 2009). A reduction of the mean frequency in the EMG power spectrum has been considered an indicator of pain and muscle damage in other conditions, specifically after eccentric exercises (Chen, 2003; Felici et al., Kawczynski et al., 2007; Linnamo et al., 2000; Sbriccoli et al., 2001). We speculated that cross country skiing athletes with a history of anterior compartment pain may adapt their muscle activation patterns and that such changes may appear as disproportionate increases of the EMG intensity with increased effort level of skating or as a shift of the EMG power spectrum towards lower frequencies.

The purpose of this study was therefore to identify differences in the muscle activation patterns between cross country skiers with a history of anterior compartment pain and pain-free controls. It was hypothesized that,

(H1) when increasing the skating effort from moderate to intense, skiers with a history of anterior compartment pain show a disproportionate increase in the muscle activation level of the affected muscle (tibialis anterior).

(H2) the EMG power spectrum of the affected muscle differs between the groups with the symptomatic group showing a shift towards lower frequencies compared to the control group.

Methods

Subject Population

Twelve cross-country skiing athletes who competed in national and international races volunteered for this study (age 18 ± 2 years, height 175 ± 13 cm, weight 69 ± 10 kg). All subjects had given informed written consent prior to participating and the study was approved by the appropriate institutional ethics review board. Before the tests, all subjects filled out a questionnaire assessing a) the training intensity and the level of participation in races, b) the frequency, severity, and symptoms of anterior lower leg pain they had experienced during skating, and c) if the subject had been diagnosed with CACS by a physician or had undergone fasciotomy to treat CACS. The results of these questionnaires are summarized in Table 1. The subjects were then divided into three groups based on the frequency and severity of their pain symptoms: the symptomatic group consisted of 5 subjects who had reported that they often suffered from pain with typical CACS symptoms. Both, CACS patients who had undergone surgical treatment and subjects who had not undergone surgical treatment were categorized as symptomatic. The control group consisted of 4 healthy subjects who reported that they were free of any pain during skating. Three subjects reported that they had sometimes suffered pain in the lower leg, but their diagnosis was not without ambiguity (Table 1). Therefore, they were neither included in the symptomatic nor the control group. Their results were analyzed individually and then compared with the results of the two other test groups.

Measurement Protocol

Measurements were carried out on groomed cross-country trails and subjects used their own skiing equipment. Each subject individually warmed-up before the measurements were carried out. Subjects skated 12 trials of 30 second duration with different skating speed in the V2 skating technique. The skating speed was self-selected such that the skating effort complied with the “effort zones” defined in Table 2. All subjects had used these zones in their training plans. Two different conditions were compared in this study: in the first condition the subjects skated on even ground with a speed categorized as “zone 2” (heart rate 70%-80% of the maximum heart rate). In the second condition the subjects skated on even ground with a speed categorized as “zone 4” (heart rate 90%-100% of the maximum heart rate). Heart rate monitors were used to ensure that the heart rate was within the defined range.

Recording of the myoelectric signals

EMG signals were recorded on the muscles *tibialis anterior*, *peroneus longus*, *soleus*, *gastrocnemius medialis* and *gastrocnemious lateralis* using round pregeled disposable Ag_2Cl bipolar surface EMG electrodes with a inter-electrode spacing of 22 ± 1 mm (Myotronics Inc., Kent, WA, USA). The electrodes were connected to single differential amplifiers. The EMG signals were amplified 2500 times and band path-filtered between 10-700Hz before being recorded by a data logger. In the symptomatic group the leg that had suffered more severe symptoms was instrumented. In the control group the dominant leg was instrumented. Shaving, abrasion and cleansing with rubbing alcohol prepared the skin in the region of the electrode sites. The electrodes were placed on the skin overlying the muscles according to the guidelines given by the SENIAM project (Hermens et al., 2000). The electrodes, cables, and amplifiers were secured to the skin using medical tape. In addition, an accelerometer was attached to the back of the ski boot of the instrumented leg. The recording equipment was carried by subjects in a backpack.

Analysis

Individual steps were identified by determining the toe-off motion in the acceleration of the foot. Five consecutive steps were selected in each trial for further analysis.

Each accepted EMG signal was submitted to a time/frequency analysis using 13 non-linearly scaled wavelets calculated according to von Tscharner (2000). The wavelet centre frequencies covered the range between 6.9 and 542

Hz. An example of a wavelet transformed EMG signal is shown in Figure 1. It displays the intensity/power *P(cf,t)* (grey scale) as a function of time t (abscissa) and wavelet center frequency cf (ordinate). The relative increase of power per step due to an increase of skating effort, P_4/P_2, the distribution of power among the frequency bands (*power spectrum*), and the *normalized wavelet intensity patterns* were compared between subject groups. They were calculated as follows.

The *average power per step* P_{av} was determined by first adding the power of all wavelet bands (cf_1-cf_{13}) to a total power at time t and then averaging the result over the whole step duration t_{step}:

$$P_{av} = \frac{1}{t_{step}} \int_{t=0}^{t_{step}} \sum_{cf_1}^{cf_{13}} P(cf,t)$$

The muscle activation intensity for skating one step in zone 2 or zone 4 was then quantified for each subject S by calculating the mean of the average power per step: $P_{S,\ zone\ i} = mean_{steps\ in\ zone\ i}\ (P_{av})$. The relative increase P_4/P_2 of power per step due to an increase of the skating effort from zone 2 to zone 4 was calculated by dividing $P_{S,\ zone\ 4}$ with $P_{S,\ zone\ 2}$. These relative increases of power per step were compared between subject groups by calculating the mean and the range (minimum and maximum) of P_4/P_2 over all subjects of a group.

The *EMG spectra* were calculated by averaging the intensities determined in each wavelet band over the step duration t_{step} and then normalized by dividing the average power per step:

$$P(cf) = \frac{1}{P_{av} \cdot t_{step}} \int_{t=0}^{t_{step}} P(cf,t)$$

These normalized EMG spectra represented the intensity distribution over the thirteen frequency domains:

$$\sum_{cf_1}^{cf_{13}} P(cf) = 1$$

For each effort zone the mean spectra of all steps of a subject S were calculated by $P(cf)_{S,\ zone\ i} = mean_{steps\ in\ zone\ i}(P(cf))$ and then compared between the subject groups by averaging the mean spectra over all subjects of a group.

Normalized wavelet intensity patterns were calculated by dividing the power $P(cf,t)$ by the average power per step P_{av} and the step duration t_{step}:

$$P_{norm}(cf,t) = \frac{P(cf,t)}{P_{av} \cdot t_{step}}$$

All steps recorded during skating in the same effort zone were averaged over the same subject and then averaged over all subjects of the same group. Differences in the muscle activation patterns between the symptomatic group and the control group were visualized by calculating a *differential wavelet pattern* $\Delta P(cf,t)$ subtracting the averaged normalized wavelet intensity patterns of the control group from that of the symptomatic group:

$$\Delta P(cf,t) = P_{norm}^{sympt}(cf,t) - P_{norm}^{control}(cf,t)$$

Statistics

Due to the small sample size Cohen's d using the pooled variance was used to compare P_4/P_2 between groups. According to Cohen (1992), group differences with effects sizes of $d > 0.8$ were considered as large. Group differences in the EMG spectra and the assessment to which group the subjects J, K, L might fit were analyzed by χ^2-goodness of fit test (Bevington, 1969). The probability associated with χ^2 was calculated considering 12 degrees of freedom (due to 13 wavelets). An α-level of 0.05 was considered as statistically significant.

Results

Differences between symptomatic and control group

In both subject groups all muscles showed an increase in the *average power per step* P_{av} (*P4/P2 > 100%)* when increasing the effort level from zone 2 to 4 (Table 3). Statistically the differences were large for the muscles *tibialis anterior*, *peroneus longus* and *gastrocnemius lateralis*. However, it should be noted that the variability between subjects and the within-subject variability between different steps (not shown in the Table) were large compared to the difference between the mean values. The ranges over which the total EMG intensities varied overlapped largely between the two test groups.

The averaged frequency spectra of the EMG signals *P(cf)* calculated for the whole step cycle when skating in zone 2 are shown in Figure 2. Significant differences between the two groups were only found in the *tibialis anterior* muscle ($\chi^2(12) = 66.75$, $p < 0.001$). All subjects in the symptomatic group showed a mono-modal frequency spectrum in the tibialis anterior EMG, while three of the four subjects in the control group showed a bi-modal EMG frequency spectrum. Differences in the power spectra of the muscles *peroneus longus*, *soleus*, *gastrocnemius medialis* and *gastrocnemious lateralis* were not significant (χ^2(12)

= 15.70, p = 0.21; $\chi^2(12)$ = 4.25, p = 0.98; $\chi^2(12)$ = 9.35, p = 0.67 and $\chi^2(12)$ = 5.64, p = 0.93, respectively).

The *normalized wavelet intensity patterns* of the muscle *tibialis anterior* when skating in zone 2 are shown for the symptomatic and the control group in Figure 3 on the top and in the middle, respectively. In both subject groups, three periods of high muscle activation levels were visible within the step cycle: 1) in the swing phase approximately between 0 and 30% of the step cycle, 2) when the subjects glided on one leg approximately between 40 and 60%, and 3) directly before the push-off phase when the ski glided outward between 80 and 90% of the step cycle. The *differential wavelet pattern* (Figure 3, bottom) showed that the control group activated the *tibialis anterior* with higher intensity than the symptomatic group in the early swing phase (5-20% of the step cycle), while the symptomatic group showed higher activation levels towards the end of the swing phase (20-30% of the step cycle). Throughout the step cycle, the control group showed higher intensities in the high frequency bands (271Hz and higher) compared to the symptomatic group. This was particularly obvious in the gliding phase (40-60%), but also in the last activation phase of the step cycle (80-90%).

Classification of subjects with uncertain diagnosis

The relative increases of power per step, *P4/P2*, determined for the five muscles of subjects J, K, L, who were not included in the symptomatic or the control group, did not allow an unambiguous classification. However, the power spectra *P(cf)* of the subjects' *tibialis anterior* muscles allowed a clear classification: subject J and K's power spectrum fit well to the power spectrum found in the symptomatic group ($\chi^2(12) = 8.15$, $p = 0.77$ and $\chi^2(12) = 13.39$, $p = 0.34$) while it was significantly different from the control group ($\chi^2(12) = 153.5$, $p < 0.001$ and $\chi^2(12) = 143.9$, $p < 0.001$). Subject L fit to the control group ($\chi^2(12) = 14.01$, $p = 0.30$) but not to the symptomatic group ($\chi^2(12) = 86.33$, $p < 0.001$).

Discussion

EMG Intensity

It was hypothesized (H1) that subjects with a history of anterior compartment pain would show a disproportionate increase in the muscle activity of the tibialis anterior when increasing skating effort from moderate to intense. The relative increases of power per step *P4/P2* found in this study seem to support this hypothesis. Large effects were found not only in the tibialis anterior, but also in the peroneus longus and in one of the tibialis' antagonists, the gastrocnemius lateralis. This might be an indication that the increase of muscle activation might be due to a co-contraction of several muscle groups. However, a post hoc analysis of the statistical power of the P4/P2-differences between subject groups did not yield a power larger than 0.5. More research is therefore necessary before this result and its interpretation may be considered conclusive.

Frequency Spectrum of the EMG

The second hypothesis (H2) stated that the EMG spectra of the tibialis anterior would differ between the groups with the symptomatic group showing a shift towards lower frequencies compared to the control group. This hypothesis was also supported by the results of this study. The difference between the spectra of the two groups was highly significant. Specifically, subjects with CACS pain symptoms showed mono-modal frequency spectra with higher intensity contributions to the spectrum in the lower frequency domains. Subjects without pain symptoms tended to have bi-modal spectra and higher intensity contributions in the frequency bands above 271 Hz (wavelet 9). Several previous studies (Karlsson and Gerdle, 2001; von Tscharner and Goepfert, 2006; von Tscharner et al., 2003; Wakeling et al. 2002) suggested that the most plausible explanation for such differences in the shape of the EMG power spectrum could be a difference in the recruitment of fibers of a specific type. Subjects in the symptomatic group, who showed a mono-modal EMG frequency spectrum, may have activated predominantly the type I (slow twitch) muscle fibers, while the subjects in the control group, who showed a bi-modal EMG spectrum, may have activated both, type I and type IIb/x (fast-twitch) muscle fibers.

The trials in our study were short and the muscle load was not higher than the load during the subjects' daily practice. Moreover, none of the subjects reported pain during the measurements and subjects who had already undergone surgery showed the same EMG spectra as subjects who still experienced pain regularly. A shift of the EMG spectrum to lower frequencies in the symptomatic group could therefore be evidence of persistent adaptations of the muscle recruitment patterns, e.g. as a neural protective mechanism to protect fast twitch fibers (Chen, 2003), or an indication of selective damage of fast twitch fibers (Felici et al., 1997; Linnamo et al., 2000; Valderrabano et al. 2006). One could speculate that the reduced recruitment of one muscle fiber type might also play a role in the aggravation of CACS since the load and the likelihood of injury for the remaining active fibers may potentially increase.

Classification of subjects with uncertain diagnosis

Sbriccoli et al. (2001) suggested that a shift to smaller frequencies in the surface EMG power spectrum might be used as early indicator of muscle damage. In cross country athletes that are at risk of developing CACS this might be particularly useful, because potential CACS patients might be able to avoid the worst symptoms by reducing their training intensity at an early stage. In this study three subjects could not unambiguously be classified as symptomatic, because they reported some lower leg pain but did not suffer from these symptoms as frequently as the subjects in the symptomatic group. However, the comparison of their tibialis anterior power spectra with the mean spectra of the symptomatic and the control group allowed an unequivocal classification. We plan to follow up on these three subjects in the next years to determine if they will in fact develop further CACS symptoms.

Differences in Muscle Activation within the Step Cycle

The muscles of the anterior compartment are highly involved in dorsiflexion of the foot. In the cross country skiing step cycle dorsiflexion is functionally important during the swing phase of the leg (Gertsch et al., 1987) and when stabilizing the ankle during the gliding phase (Smith, 1992). It has been speculated (Lawson et al., 1992) that anterior compartment pain and CACS might be caused by the work that the tibialis anterior has to do during the swing phase in order to lift the ski off the ground, however, so far no conclusive evidence for this assumption could be provided (Lawson et al., 1992). The *differential wavelet pattern* $\Delta P(cf,t)$ shown in Figure 3 indicated some group differences in the swing phase (10-30% of the step cycle) related to the timing of the muscle activation, however, it also showed clear group differences in the gliding phase (40-60%) related to the frequency content of the EMG signal. In the future one should therefore consider both phases when investigating causes or effects of CACS. Biomechanical analyses of the V2 skating technique show that at around 50% of the step cycle only the instrumented leg is in contact with the ground (Smith, 1992). The other ski and the two poles are in a swing phase. The activation of the tibialis anterior in this phase therefore most likely contributes to stabilize balancing on this leg. The differences in the activation patterns between the two test groups might therefore indicate that the neuromuscular control of balance represents a key issue when studying CACS.

Limitations of this study

The major limitation of this study was the small sample size. The reason for the small sample size was that mainly elite cross country skiing athletes are affected by CACS. In order to obtain homogeneous and matching symptomatic and control groups we decided to only recruit young athletes who compete in national competitions and who practice several hours every day. Unfortunately such athletes are difficult to come by. However, despite the small sample size, clear and statistically significant differences were obtained in the EMG spectra.

A second limitation specific to the analysis of the power per step P_{av} and of *P4/P2* was the large variability observed not only between subjects but also between different trials of the same subject. Future studies might be able to improve the statistical power of the P4/P2-analysis by reducing this variability, for example, by having the subjects skate on a treadmill where speed and other influencing variables can be controlled more accurately.

Conclusions

There are two important outcomes of this study that have never been reported before in patients suffering from anterior compartment pain or CACS patients:

1) Athletes with a history of anterior compartment pain appear to show a different frequency content in the muscle activation signal of the tibialis anterior (mono-modal versus bimodal frequency content). The most likely explanation for this observation is that the athletes with a history of pain recruit different fiber types.
2) The differences were most obvious in the gliding phase, when the subjects were supported only by the instrumented leg. This suggests that the neuromuscular control of balance may play an important role in anterior compartment pain and potentially in the development of CACS.

Both of these results may prove to be clinically useful in the future. The first result might help develop an early indicator of athletes that are at risk of developing CACS. If this succeeds then it might be possible to help subjects avoiding CACS, for example, by reducing the training intensity at an early stage. The second result might help to further understand what movements are critical for the development of CACS. This might help establishing prevention programs, for example, specific balance training exercises.

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Tables

Table 1. Training intensity and pain symptoms of the subjects included in the study.

Table 2. Target HR training zones as used by the participating subjects to plan their training program.

Table 3. Relative increase of power per step, P_4/P_2, due to an increase of the skating effort from zone 2 to zone 4.

Table 1. Training intensity and pain symptoms of the subjects included in the study.

Subject	Group	Gender	Training (hr/ week)	Skiing (hr/ week)	had Surgery?	Self-reported pain symptoms
A	Sympt.	M	15	14	yes	Before surgery: pain: always when exercising; eventually stops after exercise; affected performance results;
B	Sympt.	F	10	8.5	no	pain: often; worsens with exercise; eventually stops after exercise; affected race performance; missed race due to pain; 3 months no training due to pain;
C	Sympt.	M	12	12	no	pain: often; worsens with exercise; does not stop after exercise;
D	Sympt.	M	15	13	yes	pain: sometimes (after surgery); worsens with exercise; does stop after exercise; affected race performance; missed race due to pain; missed training due to pain;
E	Sympt.	M	15	12	no	pain: often; worsens with exercise; does not stop after exercise; affected race performance;
F	Control	M	14	12	no	no symptoms
G	Control	F	12	8	no	no symptoms
H	Control	F	12	10	no	no symptoms
I	Control	F	10	6	no	no symptoms
J	-	M	20	20	no	pain: sometimes; does not stop after exercise;
K	-	M	15	12.5	no	pain: sometimes; does not stop after exercise; affected race performance; missed training due to pain;
L	-	F	18	9	no	pain: sometimes;
mean			14.0	11.4		
STD			3.0	3.6		

Table 2. Target HR training zones as used by the participating subjects to plan their training program.

Zone	Training Type	Heart Rate, % of Max	Breathing	Pace
1	Distance/Recovery	60-70	Very easy to talk	Slow
2	Distance/Technique	70-80	Easy to talk	Medium
3	Threshold/Steady State	80-90	Hard to talk	50 km race pace
4	VO_2 max	90-100	Very hard to talk	5 km race pace
5	Speed	n/a	Can’t talk	100 m race pace

Table 3. Relative increase of power per step, P_4/P_2, due to an increase of the skating effort from zone 2 to zone 4.

	Symptomatic group		Control group		
muscle	zone4/zone2	range max,min	zone4/zone2	range max,min	Cohen's d
tibialis	143 ±12%	157% 135%	125 ± 23%	152% 109%	1.17
peroneus	123 ±24%	145% 83%	107 ± 06%	142% 103%	0.91
soleus	135 ±27%	165% 115%	144 ± 22%	167% 119%	-0.47
gastroc. medialis	120 ± 9%	127% 114%	141 ± 37%	185% 101%	-0.77
gastroc. lateralis	167 ± 51%	225% 127%	117 ± 12%	134% 107%	1.64

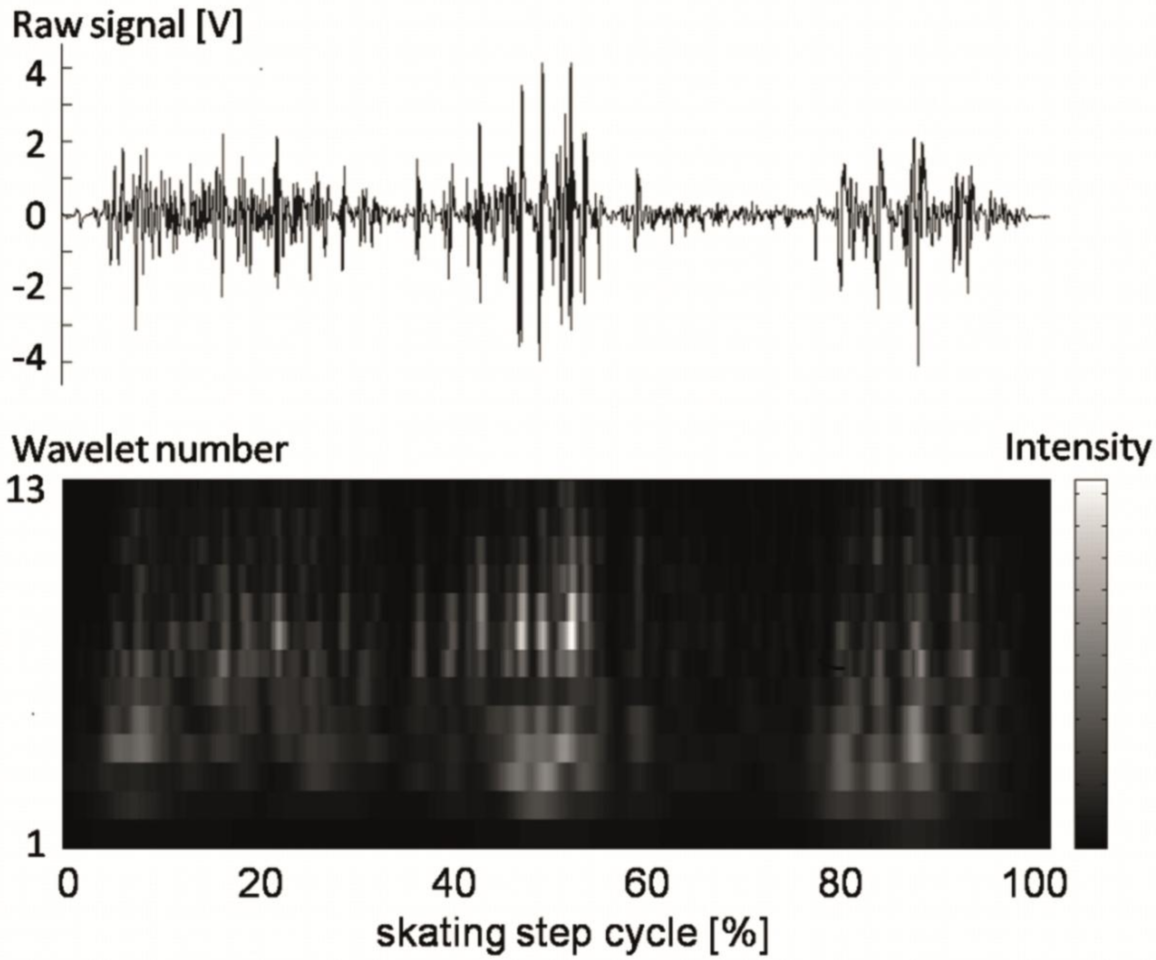
A value of 100% indicates that the total EMG intensity per step cycle did not change, lager values indicate that the intensity in zone 4 steps was higher.

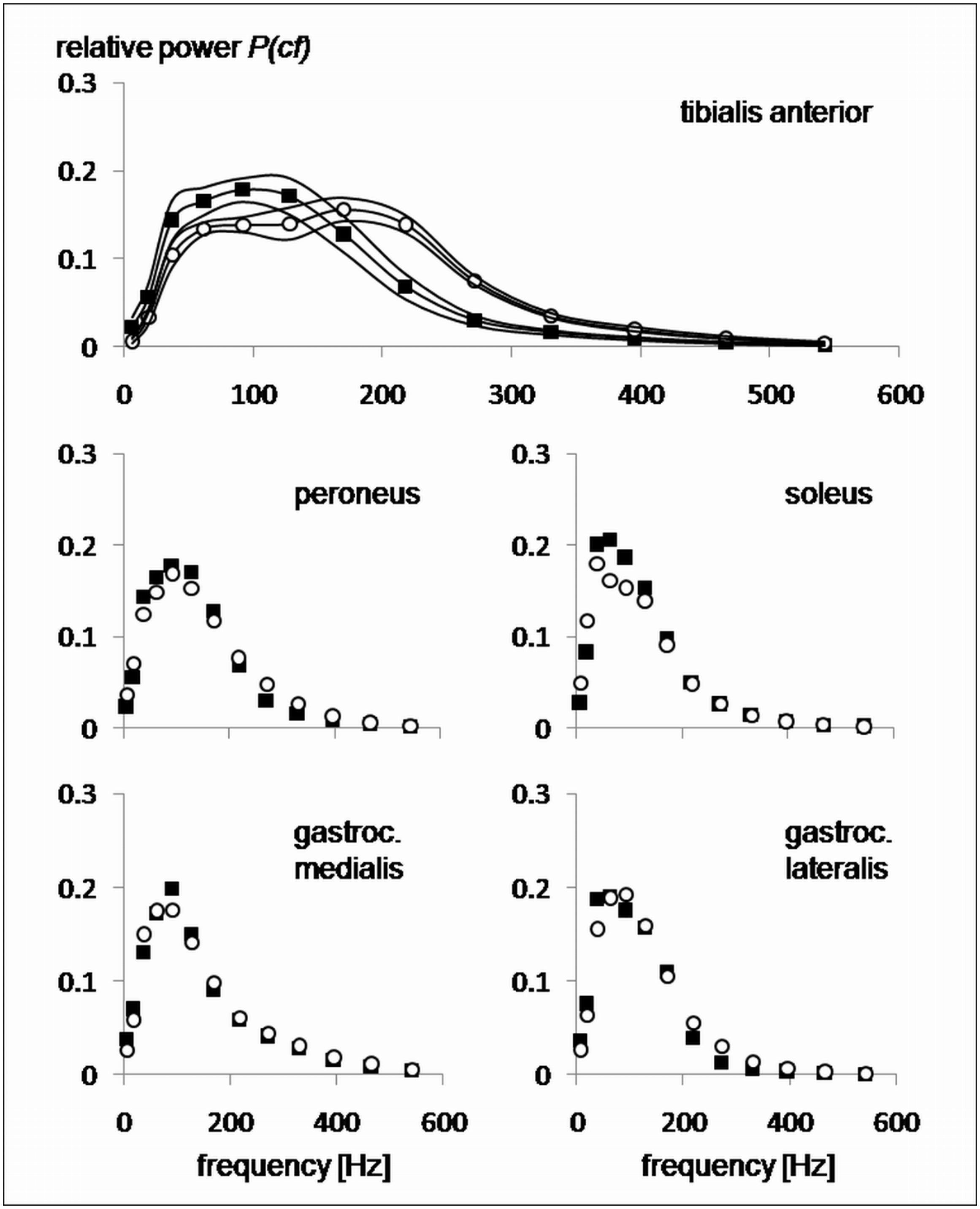
Figures

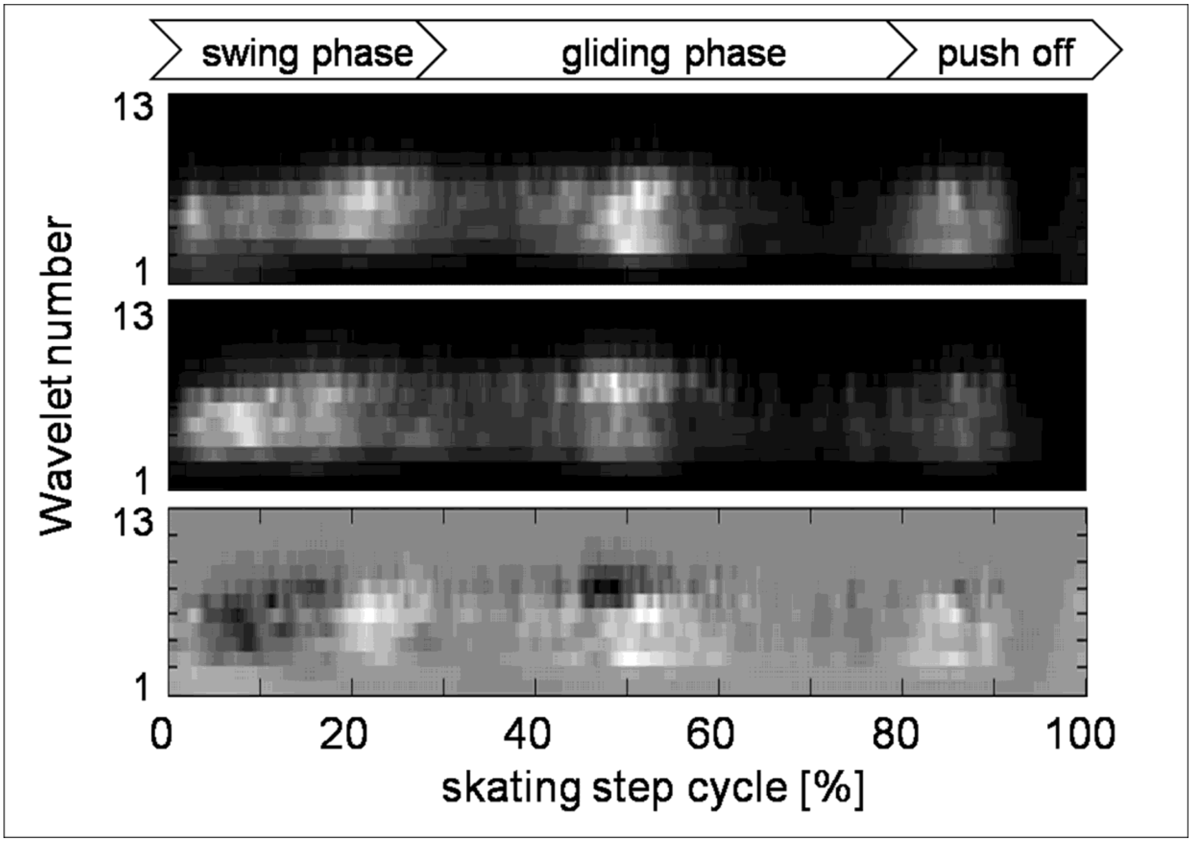
Figure 1 Illustration of a raw EMG signal measured at the tibialis anterior muscle of one subject during one skating step cycle (top) and the corresponding power *P(cf,t)* pattern obtained with the wavelet transformation (bottom). The intensity is indicated in gray scales with white corresponding to higher intensities. Both graphs use the same time scale.

Figure 2 Frequency spectra *P(cf)* of the five muscles during skating in zone 2 averaged over the subjects in the symptomatic group (black squares) and over the subjects in the control group (white circles). For the tibialis anterior the standard error of the mean (SEM) was indicated as continuous lines above and below the symbols, in the other graphs the SEM was omitted for better clarity. The goodness of fit test confirmed that only the spectra of the tibialis anterior differed significantly between the subject groups.

Figure 3 Normalized wavelet intensity patterns *P(cf,t)* of the tibialis anterior during one step cycle of skating in zone 2. Top: mean pattern averaged over the symptomatic group; middle: mean pattern of the control group; bottom: the *differential wavelet pattern* $\Delta P(cf,t)$. The white areas in the bottom graph indicate higher muscle activation intensity in the symptomatic group compared to the control group; black areas indicate higher activation levels of the control group.


Raw signal [V]
4
2
0
-2
-4
Wavelet number
13
1
Intensity
0
20
40
60
80
100
skating step cycle [%]


relative power P(cf)
tibialis anterior
0.3
0.2
0.1
0
0
100
200
300
400
500
600
peroneus
soleus
gastroc. medialis
gastroc. lateralis
0
200
400
600
frequency [Hz]
frequency [Hz]


swing phase
gliding phase
push off
Wavelet number
13
1
13
1
13
1
0
20
40
60
80
100
skating step cycle [%]