Muscle activity during recreational alpine skiing – Determined by a new methodological approach in alpine skiing surface EMG analysis

Dissertation

Zur Erlangung des Doktorats am
Interfakultären Fachbereich für Sport- und Bewegungswissenschaften
der Universität Salzburg

Eingereicht von

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Salzburg, Dezember 2010
Thank you ...

...James that you were interested on my data after the Munich presentation in 2006 and for offering your support. Furthermore thanks for the invitations to join your lab, to participate on your outstanding ideas and the friendship which rose throughout the years.

...“Hansi” for you friendship and your self-evident support throughout several project phases. Thanks for giving me the chance to participate on your outstanding ability to discuss alpine skiing results from several perspectives.

...Erich for giving me all those great opportunities to enhance my knowledge in several areas of our favourite sport – alpine skiing, and the world of sport science.

A special patience award to the “Golden Kröll girls” - No words can explain how deeply grateful I am to be a member of our family. I love you!
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Reviewing the literature concerning direct measures of muscle activity via (surface) EMG depicts three main limitations: 1.) Nearly all of the previous research on muscle activity during alpine skiing was published before carving skis were introduced, and most of these reports include competitive or expert level skiers. However, for recreational alpine skiing those “out of the date” and “foreign target group” work is still the bench mark for actual (primarily physiological) studies upon which assumptions or discussions take place; 2.) While fatiguing processes during recreational skiing are associated with increased number of injuries, to date it has not been addressed from a muscle activity perspective; and 3.) From a methodological point of view existing studies have rather simple designs and the analysis of the EMG measures quantified only in intensity (amplitudes) and time domain (timing) but never in frequency domain. Consequently, the aim of this PhD project was to enhance the knowledge of muscle activity during recreational alpine skiing by considering the three mentioned limitations of the existing alpine skiing scientific literature. Due to the efforts in performing a field study on snow, the experimental approach was to gather the necessary information within one large on snow experiment. For the analysis of the EMG the previously published approach using wavelets was chosen (introduced in 2000 by von Tscharner). This method permits the signal intensities to be simultaneously resolved in time and frequency. In particular, the frequency component of the signal allows a more in depth and functional muscle activity analysis, and has never been considered before in alpine skiing research. Within the two different main parts of the cumulative PhD Project the general quadriceps muscle function on the one hand and the influence of a sustained skiing session on muscle activity during recreational skiing on the other hand were investigated. The results and discussions are provided via two peer reviewed journal articles, two book chapters and several Congress abstracts. Furthermore, a side project in the form of a physiological peer review article was published out of the experiments. The project depicted several new insights to muscle activity for recreational skiers like:

- Contrary to previously suggested co loading of the inside leg while carving our results does not support this hypothesis.
- The ability of a situation-dependent loading (m. rectus femoris as knee extensor) and unloading (m. rectus femoris as hip flexor) of the inside leg seems to be a crucial point for recreation skiers.
- General muscular fatigue, where additional specific fibres have to be recruited due to the reduced power output of other fibres, did not occur.
- A modified skiing style towards a less functional and hence more uncontrolled skiing technique seems to be a key issue with respect to the influence on muscle recruitment for an applied, prolonged skiing session.
- The used wavelet analysis method is a powerful tool in describing muscular activity for alpine skiing in a more in depth manner. Substantial conclusions for alpine skiing were (and can be in future) drawn by the analysis of the frequency content.
Introduction

In many regions in the world, alpine downhill skiing is one of the most popular and most frequently practiced forms of winter sport. In alpine regions, this fact is of high significance above all from economic, social, and health aspects. The carving boom of the late 1990’s provided a stimulus to aid in revitalizing alpine skiing as a popular recreational sport activity during the winter season. The number of skiing days increased from 44 to 51 million (+16%) from 1999 through 2004 in Austria (Kroell et al., 2005). The National Ski Areas Association reported that nearly 7 million skiers made 58.9 million visits to ski areas in the United States during the 2005 ski season (April 2007, www.nsaa.org/nsaa/press/industryStats.asp.)

Those data show, that within the last 20 years, the ski industry created a very successful innovation with the development of the carving ski system. In ski racing as well as in recreational skiing, skis have become much shorter, their side cut has increased to a great extent and binding plates (risers) have been fixed between the ski and the binding. In addition the stiffness of the ski has also changed. This evolution has, of course, also changed the movement patterns while performing ski turns and the physiological demands on a skier; yet, it might also have changed the risk of sustaining injuries.

Research in Alpine skiing since the introduction of the carving ski system

Depending on the situation, evidence based research is not only helpful for improving the comfort, enjoyment, and performance, but also safety in alpine skiing. Performing a Pub med query for ‘Alpine Skiing’, delivered a total number of 313 papers (on 02.007.2010). The first paper which explicitly mentioned the carving ski system was a article in German by Kober and Held (1997). From 1997 to 2000 both traditional and carving skis were investigated. Since 2000, nearly all studies used carving ski equipment with different research approaches. Performing the same Pub med query as mentioned above but only considering the papers after 1999 delivered 117 entries. Excluding the papers not directly related to alpine skiing (24) reduced the number to 91 articles dealing directly with alpine skiing. According to the different research topics of these 91 articles, Table 1 serves as an overview. Half of the papers contain aspects of safety in alpine skiing, whereby 26 of the papers dealt with recreational skiing and 12 with elite skiing. Only three papers addressed qualitative sociology or psychology topics. Specific medical topics were investigated in 13 articles. Ultraviolet radiation during alpine skiing at different altitudes (Rigel et al., 2003) would be an example
for recreational skiing. Examples for elite skiing are studies by Banfi et al. (2006, 2008, 2008) investigating creatine values in various contexts.

<table>
<thead>
<tr>
<th>Research Area</th>
<th>Total Number</th>
<th>Racing/Elite background</th>
<th>Recreational background</th>
<th>Target group independent</th>
<th>From 1997 to 2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biomechanics</td>
<td>10</td>
<td>6</td>
<td>2</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Physiology</td>
<td>12</td>
<td>6</td>
<td>6</td>
<td>x</td>
<td>0</td>
</tr>
<tr>
<td>Injury topics</td>
<td>45</td>
<td>12</td>
<td>26</td>
<td>7</td>
<td>12</td>
</tr>
<tr>
<td>Conditioning</td>
<td>10</td>
<td>10</td>
<td>x</td>
<td>x</td>
<td>5</td>
</tr>
<tr>
<td>Sociology / Psychology</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>x</td>
<td>1</td>
</tr>
<tr>
<td>Specific medical topics</td>
<td>13</td>
<td>6</td>
<td>7</td>
<td>x</td>
<td>2</td>
</tr>
<tr>
<td>Not related to alpine skiing</td>
<td>24</td>
<td></td>
<td></td>
<td></td>
<td>17</td>
</tr>
<tr>
<td>Total</td>
<td>117</td>
<td>42</td>
<td>42</td>
<td>9</td>
<td>42</td>
</tr>
</tbody>
</table>

Table 1: Pubmed search for 'Alpine Skiing' (02.07.2010) - Papers from 2000 to 2010

The conditioning of/for alpine skiers was part of 10 studies and interestingly, all of them were in the field of ski racing (recent papers e.g.: Patterson et al., 2009, Gross et al., 2010, Breil et al., 2010). While the conditioning studies often use non-skiing measures to improve skiing abilities, another 12 paper investigated physiological aspect during alpine skiing. Among these studies both elite skiing (6) and recreational skiing (6) were represented in a balanced proportion. In terms of physiology of alpine ski racing, just recently two review papers were published (Turnbull et al., 2009, Ferguson, 2010). The review of Turnbull et al (2009) comprises 30 years of research and includes 29 on-snow investigations of specific physiology relating to the various ski racing disciplines, nine off-snow investigations of physiological capacities of ski racers of varying ability and four review articles. Ferguson et al (2010) describes the limitations to performance during alpine skiing from a skeletal muscle perspective by explaining the current understanding of muscle function during alpine skiing and depicting the impact on muscle fatigue. Examples of physiological studies among recreational skiers are the studies by Seifert et al (Seifert et al., 2005, Seifert et al., 2006) dealing with fluid and energy supplementation, or Scheiber et al (Scheiber et al., 2009) investigating the physiological response of older recreational skiers.

In the area of biomechanical alpine skiing research, 10 Studies were published in the last 10 years and the primarily target groups were racers and elite skiers. The only biomechanical paper which yields explicit results on recreational skiers (except the papers published for this
Thesis) is the paper by Scheiber et al. (2010) which investigated in a combined approach biomechanical and physiological aspects of older recreational skiers. Heinrich et al. (2009) and Benoit et al. (2005) completed research for a better understanding of equipment used during alpine skiing with application on both, racing/elite skiing and recreational skiing. Three out of the 10 papers deal with kinematic methods and application to high level ski racing (Supej, 2010, Federolf et al., 2008, Supej, 2008). Müller and Schwameder (2003) reviewed the considerable changes in equipment design and movement patterns since the introduction of carving skis and matched these developments by methods of analyzing movements in field conditions. They have yielded new insights into the skills of the carving turn of elite skiers by using electromyography, kinetic and kinematic methods. Tomazin et al. (2008) and Clarys et al (2001) studied biomechanics of racers and elite skiers from a muscle functional perspective.

**Research on Muscle Activity in Alpine Skiing up to now**

In order to appreciate the limitations in alpine skiing performance, the type of contraction and level of activity of the main muscle groups involved and the subsequent consequences should be considered (Ferguson, 2010). Furthermore it is suggested that the understanding of muscle function and muscle activity in various skiing situations would provide useful information pertaining to skill acquisition, appropriate movement progression, and conditioning for skiers. It may also have application in equipment design. In addition the awareness of movement patterns may help reduce the incidence of injury (Hintermeister, 1997).

For a long time research measuring muscle activity has been helpful in providing a basic understanding of the response of the muscular system during skiing. Karlsson et al. described already in 1978 differences in electromyography (EMG) between a recreational skier and a competitive skier while skiing a slalom course (Karlsson et al., 1978). Muscle activity of the competitive skier was more dynamic, with discrete bursts of activity, while the recreational skier displayed more continuous EMG activity at a lower intensity. Maxwell and Hull (1989) compared loads measured from a dynamometer between the ski and boot with EMG activity from six muscles crossing the knee joint. Performance criteria for ski bindings were recommended based on knee loads.

Performing another Pubmed query with ‘Alpine Skiing Muscle Activity’ and ‘Alpine Skiing EMG’ resulted in 19 articles whereby only 15 are directly related to alpine skiing muscle function (papers created among the current PhD Project not included). Three more papers (Senner et al., 1995, Menke and Bodem, 1987, Schaff and Hauser, 1987) had very specific
topics and do not provide information for a more in depth understanding of muscle activity in alpine skiing. Hence there were 12 papers left which help improve the understanding of muscle activity and therefore muscle function during alpine skiing (Table 2).

<table>
<thead>
<tr>
<th>Year</th>
<th>Author</th>
<th>Titel</th>
<th>Journal</th>
<th>PM ID</th>
</tr>
</thead>
<tbody>
<tr>
<td>2001</td>
<td>Clarys JP et al</td>
<td>The influence of geographic variations on the muscular activity in selected sports movements</td>
<td>J Electromyogr Kinesiol</td>
<td>11738957</td>
</tr>
<tr>
<td>1994</td>
<td>Müller E</td>
<td>Analysis of the biomechanical characteristics of different swinging techniques in alpine skiing</td>
<td>J Sports Sci</td>
<td>8064973</td>
</tr>
<tr>
<td>1989</td>
<td>Maxwell SM, Hull ML</td>
<td>Measurement of strength and loading variables on the knee during Alpine skiing</td>
<td>J. Biomech</td>
<td>2808444</td>
</tr>
<tr>
<td>1988</td>
<td>Andersen RE et al</td>
<td>Physiology of Alpine skiing</td>
<td>Sports Med</td>
<td>3067309</td>
</tr>
</tbody>
</table>

Table 2: Pub med search for 'Alpine Skiing EMG’ and 'Alpine Skiing muscle Activity' (02.07.2010) - Papers investigating explicit muscle activity during alpine skiing

Looking at publication dates of those papers it is noticeable that there have been no papers since 2003 (Mueller and Schwameder, 2003) investigating muscle activity during alpine skiing, and just one other paper where one can assume that carving skis were used (Clarys et al., 2001). Furthermore it is noticeable that since 1995 only one paper investigated muscle activity during recreational alpine skiing (Hintermeister et al., 1997). All other studies were performed with elite skiers or racers. Even though muscle activity during skiing in general was more thoroughly studied between 1994 and 1999 (six papers), one gets the impression now that now with carving skis, research on muscle activity has a low priority.

With regard to the content of the previous work, one consistent finding is a high level of effort by the knee extensor muscles during skiing and this activity is dominated by eccentric contractions (Berg et al., 1995, Clarys et al., 2001). Several authors have reported that muscle contraction forces can reach upwards of 100-150% of maximal voluntary contraction (MVC) in the outside leg when making a turn (Berg et al., 1995, Hintermeister et al., 1997). Functional differences were clearly observed within the knee extensor muscles. The substantially higher vastii EMG activity in the outside leg compared to the inside leg confirms
the generally accepted notion of a predominantly unilateral use of the knee extensors during alpine skiing. The contrasting biphasic EMG pattern of the m. rectus femoris suggests that this two joint muscle serves a dual purpose, both as knee extensor during the outside ski phase (outside leg) and as a hip flexor during the inside ski phase (inside leg) (Berg et al., 1995). Müller and Schwameder (2003) showed that the predominantly unilateral use of the knee extensor muscles has changed towards a bilateral use due to the equipment changes. Therefore an active co-loading of the inside leg while using carving skis has been suggested (Note, Müller and Schwameder investigated expert level skiers only). Clarys et al. (2001) investigated the influence of slope inclination on muscle activity during expert level skiing and suggested that the inclination of the slope is an important discriminating factor for muscle activity. The results indicated that muscular activity increased with increasing slope angle. It should be noted that data were presented as grouped over all muscles as each muscle analyzed separately did not allow for the detection of a possible topographical influence on muscle activity.

**Methodological approaches in alpine skiing muscle activity research up to now**

To evaluate muscle activity during alpine skiing surface EMG seems to be an appropriate tool and was therefore already used in several studies. Table 3 serves an overview of the different methodological approaches used in alpine skiing EMG studies since 1995. The numbers of subjects varied between case studies (Müller and Schwameder, 2003) up to n=31 (Clarys et al., 2001) whereas only one more study has a sample size higher than 10 (Berg and Eiken, 1999) and all others have 8 or less. The fact that sample sizes are so low somehow reflects that the effort to collect EMG data in the field is large. Next to the sample size it is also of note how many movement cycles, respective turns or double turns, are pooled for getting a representative EMG value for each subject. The considered numbers of turns vary between only 3 (Hintermeister et al., 1995, 1997, Zeglinksi et al., 1998) and 20 (Berg et al., 1995). A number under 10 seems to be insufficient to get a representative subject value, and hence some of the papers have limitations not only from a subject point of view, but also from the amount of data per subject.

Concerning the chosen muscle, one can observe that in the alpine skiing EMG literature mainly three different groups of muscles are of interest: **LOWER LEG**: m. tibialis anterior (TA), m. gastrocnemius medialis(MG), m. peronaeus longus (PE); **THIGH**: m. vastus medialis (VM), m. vastus lateralis (VL), m. rectus femoris (RF), m. semimembranosus and m. semitendinosus as medial hamstrings (MH), m. biceps femoris (BF), adductors (AD), m.
gluteus maximus (GM); **TRUNK**: m. rectus abdominis (RA), external obliques (EO), erector spinae (ES). Not surprisingly, for a weight bearing activity like alpine skiing, thigh muscles seem to be the primarily studied group since all papers contained at least the knee extensor group.

<table>
<thead>
<tr>
<th>Author</th>
<th>Sample Size</th>
<th>Muscles</th>
<th>Amplitude parameter</th>
<th>Time parameter within a turn or double turn</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003 Müller E, Schwameder H</td>
<td>N=1; number of turns per subject = 6</td>
<td>VM, VL, RF</td>
<td>Peak Normalization, Averaged rectified EMG amplitude</td>
<td>No analytic stats; Descriptive Results: EMG Traces from overall Inside Leg and outside Leg and partitioned into initiation and steering phases</td>
</tr>
<tr>
<td>2001 Clarys JP et al</td>
<td>N=31; number of turns per subject = no information</td>
<td>VL, VM, TA, BF, RF,</td>
<td>MVC Normalization, Integrated EMG (IEMG) pooled of all muscles</td>
<td>Analytic Stats: mean over the overall outside Leg turn, not partitioned Almost no descriptive Results, hence no EMG Traces</td>
</tr>
<tr>
<td>1999 Berg HE Eiken O</td>
<td>N=16; number of turns per subject = 5-11</td>
<td>VL, VM</td>
<td>MVC Normalization, Averaged EMG amplitude</td>
<td>Analytic Stats: Inside Leg and outside Leg, each concentric and eccentric Phase partitioned into two parts No descriptive Results, no EMG Traces</td>
</tr>
<tr>
<td>1998 Zeglinksy CM et al</td>
<td>N=5; number of turns per subject = 3</td>
<td>PE, TA, VM, BF, AD, GM, ES</td>
<td>MVC Normalization, Peak Amplitudes, Average Amplitudes</td>
<td>Analytic Stats: mean over the overall outside Leg turn; Partitioned into initiation and turning phases Descriptive Results: EMG amplitude Traces</td>
</tr>
<tr>
<td>1997 Hintermeister RA et al</td>
<td>N=6; number of turns per subject = 3</td>
<td>AT, MG, VL, VM, RF, MH, BF, AD, GM, RA, EO, ES</td>
<td>MVC Normalization, RMS Peak Amplitudes, RMS Average Amplitudes</td>
<td>Analytic Stats: mean over the overall outside Leg turn, not partitioned Descriptive Results: EMG amplitude Traces</td>
</tr>
<tr>
<td>1995 Hintermeister RA et al</td>
<td>N=7; number of turns per subject = 3</td>
<td>AT, MG, VL, VM, RF, MH, BF, AD, GM, RA, EO, ES</td>
<td>MVC Normalization, RMS Peak Amplitudes, RMS Average Amplitudes</td>
<td>Analytic Stats: mean over Outside Leg turn; Partitioned into initiation – transition – completion phases Descriptive Results: EMG amplitude Traces</td>
</tr>
<tr>
<td>1995 Berg HE et al</td>
<td>N=8; number of turns per subject = 20</td>
<td>VM, VL, RF</td>
<td>MVC Normalization, Averaged EMG amplitude of 20 double turn</td>
<td>Analytic Stats: Inside Leg and outside Leg, each concentric and eccentric Phase partitioned into two parts No descriptive Results, no EMG Traces</td>
</tr>
</tbody>
</table>

Table 3: Overview of the Methodological approaches in alpine skiing EMG research

From a methodological point of view up to now amplitude in the time domain has been the primary EMG variable studied in alpine skiing. According to De Luca (1997) in the time domain two parameters are commonly used: the root mean squared (RMS) value and the average rectified value. For EMG signals detected during voluntary contractions the RMS value seems to be more appropriate because it represents the signal power and thus has a clear physiological meaning. On the other hand the average rectified value is a measure of the area
under the signal and hence does not have a specific physical meaning (De Luca, 1997). Hence it is quite surprising that only the studies by Hintermeister et al. out of the listed studies in Table 3 used RMS value while all others use rectified amplitude values.


Table 4: Congress abstracts using the methodological approach of mean frequency of the power spectrum by Kröll et al. (2005, 2006)

Due to the involvement of different muscle fibre types (slow twitch and fast twitch fibres) and their different motor action potentials, the frequency of an EMG signal contains additional information about muscle fibre activation. When a muscle is active, faster fibres generate higher frequencies than slow fibres within the given signal (Wakeling, 2009). The mean frequency of the power spectrum, calculated by a Fourier transformation, was used by Ushiyama et al. (2005) and Kröll et al. (2005, 2006, Table 4) to evaluate fatigue during alpine

<table>
<thead>
<tr>
<th>Table 4: Congress abstracts using the methodological approach of mean frequency of the power spectrum by Kröll et al. (2005, 2006)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Due to the involvement of different muscle fibre types (slow twitch and fast twitch fibres) and their different motor action potentials, the frequency of an EMG signal contains additional information about muscle fibre activation. When a muscle is active, faster fibres generate higher frequencies than slow fibres within the given signal (Wakeling, 2009). The mean frequency of the power spectrum, calculated by a Fourier transformation, was used by Ushiyama et al. (2005) and Kröll et al. (2005, 2006, Table 4) to evaluate fatigue during alpine skiing.</td>
<td></td>
</tr>
</tbody>
</table>
skiing. The disadvantage of this method is the collapse in the temporal aspects of the signal (von Tscharner, 2002). Kröll et al. (2005) collapsed the whole movement from 1200 ms to 500ms of activity from the outside leg during a turn. This means that some functional phases are ignored (inside leg, edge changing, loading and unloading characteristics of the ski) and only partial applicability of the method for complex muscle recruitment is given (Table 4).

Relevance on a new study on muscle activity during recreational alpine skiing

Although muscle activity research is still the basis for assumptions and discussions of actual biomechanical and physiological papers, the related publication are dated and done primarily on expert level:

As initially mentioned, there have been considerable changes in equipment design and movement patterns in alpine skiing during the past decade. On an expert level, it has been shown clearly that movement patterns have changed substantially since introducing carving skis (Mueller and Schwameder, 2003). Furthermore, change seems to be omnipresent throughout all skill levels (Woerndle, 2007). From this perspective it is rather interesting that the ‘out of the date’ papers dealing with muscle activity during alpine skiing are still the bench mark to estimate the type of contraction and level of activity of the main muscle groups involved. Especially studies addressing muscle function from an ‘on-slope physiology’ or ‘conditioning for alpine skiers’ perspective, as they are still referring to results of those old muscle activity studies. For several papers (e.g.: Ferguson, 2010, Gross et al., 2010, Patterson et al., 2009, Scheiber et al., 2010, Tomazin et al., 2008, Turnbull et al., 2009), results of Berg et al. (1999, 1995), Hintermeister et al. (1995, 1997) and Zeglinski et al. (1998) provide a strong base for assumptions and hypothesis and/or for discussing the results. However, especially for recreational skiers, it seems noteworthy to question whether the same kind of muscle activity as demonstrated by expert skiers could be expected of them. Furthermore, significant changes in ski equipment over the last 15 years clearly confound possible comparisons between older studies measuring muscular activity and current results determined using current alpine ski technique.

The topic fatigue was nearly never considered from a muscle activity point of view:

Throughout the scientific literature the question of fatigue is discussed relatively frequently in terms of safety. Fatigue in recreational skiing is associated with increased risk of injury and reduced pleasure of the activity (Hunter, 1999). An increase in the number of injuries after 2-3 hours of skiing has been previously attributed to fatigue in adult skiers, with the incidence of
injury increasing as the day progresses (Meyers et al., 2007). It is interesting that the topic of fatigue is discussed in only one paper in terms of a classical muscle activity study (Tomazin et al., 2008). Others report on this topic from a relatively poor physiological perspective. In terms of fatigue and alpine skiing, a more in-depth understanding of ongoing changes in muscle activity during a prolonged skiing session would present an extension of primarily physiological measures previously reported in the literature. Knowing how skiers change their overall skiing technique based on shifts in control or altered recruitment within a muscle would provide information not only on how to improve the comfort and enjoyment, but also the safety in recreational alpine skiing (Hintermeister et al., 1997).

**Muscle activity research up to now shows several methodological limitations**

As described above, limitations can be found in overall study designs and analysis methods. For the overall study design, the most critical points are the number of subjects and turns per subject which are considered. From an EMG analysis point of view alterations can occur and should be quantified in three different domains: intensity domain, frequency domain and time domain. To the authors knowledge no papers are available so far which have considered all three different domains simultaneously. However, developments in wavelet analyses for EMG (von Tscharner, 2000, von Tscharner, 2002) over the past 10 years permit the signal to be simultaneously resolved for intensities, frequency and time.

Consequently, the relevance to study muscle activity during current recreational skiing in combination with an application of a more in depth EMG analysis method seems warranted. Studying muscle activity of recreational alpine skiers would provide useful information with both, direct application to skiers (e.g. teaching concepts, conditioning concepts) and indirect application on future research. It is assumed that the quality of research designs and interpretations on various areas of future alpine skiing research projects could be enhanced by having data on state of the art skiing technique and analyzed with current methods.
Aim of the PhD project

The limitations of previous alpine skiing muscle activity research leads to a three-part aim for the current PhD project:

1. To create a new, more in-depth, method for muscle activity studies in alpine skiing by performing a time-frequency analysis of the EMG intensities using a wavelet transformation technique which has already been applied to other activities e.g. for running and cycling.

2. To investigate functional aspects of the knee extensor muscle group in recreational skiers in different skiing situations.

3. To investigate how knee extensor muscles respond to various levels of fatigue during recreational alpine skiing with respect to recruitment and coordination of muscle activity.

Methods

Wavelet analysis for EMG signal processing (PhD project aim 1)

Traditionally the spectral properties of myoelectric signals have been characterized by their mean or median frequency and these measures have been associated with recruitment patterns and different proportions of motor unit types (Gerdle et al., 2000, Solomonow et al., 1990). The power spectrum, however, requires the measurement of the EMG signal over a substantial time span and thus the timing of the muscle is lost (Knaflitz and Bonato, 1999). This limits the time resolution for the analysis for a non-stationary signal. Furthermore, the mean and median frequency measures consider frequency components across the whole spectrum, and these may include factors in addition of the types of motor units active. (Hodson-Tole and Wakeling, 2009, Wakeling, 2009). There is not yet an absolute solution to these problems, but great progress was achieved by developments in wavelet analyses for EMG signals (von Tscharner, 2000, Karlsson et al., 2000) which permit the signal intensities to be simultaneously resolved for time and frequency. An absolute precise determination of time and frequency content of a signal simultaneously is not possible due to the uncertainty principle of signal processing. This problem means that it is impossible to determine
simultaneously both the time and frequency of a signal with any great degree of accuracy or certainty. Time-resolution is essential for the analysis of EMG signals; however, time-resolution has to be at least in the order of physiological response time of the muscle. Von Tscharner (von Tscharner, 2000) followed the concept of an event-oriented intensity analysis where events are resolved with a finite time resolution adapted to physiological functions of the myoelectric signal. This wavelet transformation for EMG signals reaches time resolutions in the order of 30ms.

Since the introduction of wavelet methodology in 2000, von Tscharner alone published 12 PubMed listed papers as first author using his wavelets with EMG specified resolution or slightly adopted wavelets. His former colleague in Calgary’s Human Performance Laboratory, Dr. James Wakeling published 20 PubMed listed papers as first author using the same or adopted wavelet approach. Numerous other papers have been published using the same approach (e.g. Hodson-Tole and Wakeling, 2007, So et al., 2009). This method has been previously demonstrated for animal model applications (e.g. Hodson-Tole and Wakeling, 2007) as well as for complex human motor tasks like running and cycling (e.g. von Tscharner, 2002, Wakeling, 2004, Wakeling et al., 2006). Due to cyclical movement patterns in a complex activity, wavelet methods also seem appropriate for alpine skiing. The principle idea of von Tscharner’s ‘Intensity analysis in time-frequency space of surface myoelectric signals by wavelets of specified resolution’ and the application for alpine skiing research is the content of the subsequent chapter:

The following section is a summarization of the methodological elements of the initial papers by von Tscharner and Wakeling (von Tscharner, 2000, Wakeling et al., 2001b, Wakeling et al., 2001a, von Tscharner, 2002):

Each wavelet acts as a band-pass Filter and enables the intensity of the signal to be calculated at different times within that specific frequency band. Wavelets in general can be seen as functions that oscillate for a short time (Figure 1, right). They must be localized in time and frequency and the integral over time must be zero. Wavelets can be represented equally in time or in frequency space and one can calculate one from the other by a Fourier transform. Figure 1 represents e.g. two different wavelets (wavelet 2 in red and wavelet 5 in blue) in frequency (left) and time space (right). The used wavelets are well defined by centre frequency, bandwidth and the time resolution. The specific values for the resulting wavelet parameters are shown in Table 1, the shape of the set of wavelet in frequency space is presented in Figure 1 (left). At the centre frequency, all wavelets have an amplitude of 1. The
shape of the wavelets was determined in a way that the sum of all wavelets should be as close as possible to a constant in a restricted frequency range of 20 to 200 Hz. The plateau like sum of all wavelets is presented via the dotted line in Figure 1 (left). Usually wavelets are derived from a mother wavelet by linear scaling. Linearly scaled wavelets keep their shape. The constructed set of wavelets by von Tscharner was produced by nonlinear scaling. The scaling was adjusted to obtain a physiologically acceptable time resolution at all frequencies considering the uncertainty principle.

![Figure 1 Modified according to von Tscharner (2000): (left) Filter-bank of 10 wavelets in frequency space (solid line). Sum of all wavelets (dotted line). (right) Wavelet 2 (red) and 5 (blue) in time space shifted by 100 and 150 ms respectively.](image)

<table>
<thead>
<tr>
<th>Wavelet number</th>
<th>Center frequency (Hz)</th>
<th>Bandwidth (Hz)</th>
<th>Time-resolution (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>6.90</td>
<td>9.77</td>
<td>76.5</td>
</tr>
<tr>
<td>1</td>
<td>19.29</td>
<td>15.63</td>
<td>59.0</td>
</tr>
<tr>
<td>2</td>
<td>37.71</td>
<td>21.48</td>
<td>40.5</td>
</tr>
<tr>
<td>3</td>
<td>62.09</td>
<td>27.34</td>
<td>31.5</td>
</tr>
<tr>
<td>4</td>
<td>92.36</td>
<td>35.16</td>
<td>26.0</td>
</tr>
<tr>
<td>5</td>
<td>128.48</td>
<td>41.02</td>
<td>21.5</td>
</tr>
<tr>
<td>6</td>
<td>170.39</td>
<td>46.55</td>
<td>19.5</td>
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<tr>
<td>7</td>
<td>218.08</td>
<td>52.73</td>
<td>16.5</td>
</tr>
<tr>
<td>8</td>
<td>271.50</td>
<td>58.59</td>
<td>15.0</td>
</tr>
<tr>
<td>9</td>
<td>330.63</td>
<td>66.41</td>
<td>13.5</td>
</tr>
<tr>
<td>10</td>
<td>395.46</td>
<td>72.27</td>
<td>12.0</td>
</tr>
</tbody>
</table>

Table 5: Von Tscharner’s Parameters of the wavelets (von Tscharner 2000)

The Wavelet analysis of EMG: The wavelet transform is the convolution of each single wavelet and the signal taken into account (EMG signal). The convolution with one wavelet can be done according to the convolution theorem as a multiplication in frequency space between the Fourier transformed (EMG) signal and the Fourier transformed wavelet. This process is equivalent to a filtering procedure. An inverse Fourier transform converts the wavelet transform of the signal from the frequency to the time domain. Repeating the wavelet transform for all wavelets is called wavelet analysis. The sum of all wavelet transforms at each time point is an approximation of the original signal within the accuracy given by the plateau variability of the Filter bank in frequency space (Figure 1, left dotted line). After the
wavelet analysis, the intensity of the EMG signal for each Wavelet is calculated. The intensity is computed for the wavelet-transformed signal by adding its square and the square of its time derivative divided by the centre frequency. In a last step a Gauss filter is used to smooth the calculated intensity. The resulting intensities are a close approximation of the power of the EMG signal contained within a given frequency band at each time point. According to De Luca (1997) the signal power is a appropriate EMG measure since it has a clear physiological meaning. Summing up the calculated intensities over all wavelets, results in a total intensity at each time point. Thus, the total intensity can be seen as an equivalent of the root mean square values of traditional EMG amplitude analysis.

Figure 2 visualizes the outcome of the process described above for an alpine skiing signal from the m. rectus femoris. The raw signal for 5 consecutive double turns is presented on the upper part of Figure 2. A double turn is defined as where the right leg is the inside leg (Figure 2; IL dotted horizontal lines) during the first turn and then is the outside leg (Figure 2; OL dotted horizontal lines) during the second turn. The start and end of each double turn were determined by using a combination of knee angle and raw EMG signals and are visualized by the red vertical lines within the raw signal chart in Figure 2. The lower part of Figure 2 depicts the wavelet transformed intensities over time of one double turn for the Wavelets 1, 3, 5, 7 and 9. This chart represents the best possible time resolution since intensities for each Wavelet (frequency band) at each time point are provided. However, to assess statistical evidence of the intensities among an experimental group it makes sense to reduce the absolute time information to a functionally acceptable amount of time windows. For the projects within this thesis the double turn was therefore divided into 10 equal time windows (Figure 2, below, vertical dashed lines). Furthermore two larger time frames were defined: overall inside leg (IL) and overall outside leg (OL). Once the desired time windows are set, intensities can be averaged for each wavelet and time window. This serves the possibility to calculate the overall average intensity pattern obtained from repetitive experiments like alpine skiing for statistical analysis.

Different ways to visualize time averaged intensity pattern were chosen for the current thesis. One is to show the result of a wavelet analysis as a grid plot (Figure 3, left). In such a plot the horizontal axis represents time information and the vertical one represents the different wavelets (centre frequency). The color indicates the intensity. However, presenting the results in a contour plot may not resolve signals of lower intensity and does not represent the variance of a signal and thus it is primarily useful for descriptive statistics. Another possibility is a plot of the time averaged intensity pattern versus the centre frequencies of the
corresponding wavelet which is termed an intensity spectrum. Intensity spectra for each time window of a double turn are plotted in Figure 3 (right). For the quantitative analysis also the total intensity and the mean frequency can be extracted from the intensity spectra. The total intensity at each time frame was calculated as the sum of the intensities within each spectrum (across wavelets 1 to 10; corresponding to frequency band 11-432 Hz), and is termed the total

Figure 2: Wavelet transformation in alpine skiing – from the raw signal to the intensity trace of selected wavelets for one double turn
EMG intensity. The mean frequency at each time frame was defined as the sum of the intensity–frequency product over wavelet domains 1-10 divided by the sum of the intensities, using the following equation:

$$\text{MeanFrequency} = \frac{\sum_{\text{Wavelet1}}^{10} (\text{Intensity} \times \text{CentreFrequency})}{\sum_{\text{Wavelet1}}^{10} \text{Intensity}}$$

Throughout the two papers the different methods of quantification and visualization were used depending on the question to be answered.

For the analysis of the fatigue part of this thesis, a combined approach of wavelet analysis and principal component technique was used. The main information is derived by the first two principal components (PC I and PC II) and explain the variation in motor unit recruitment. Additional variations in the original spectra’s (e.g. movement artifacts and motor unit synchronisation) are partitioned into lower components and hence, do not obscure the main information of interest. Therefore it is suggested that the principal component technique is more sensitive to major changes in the EMG spectra that occur during movements and locomotion (Wakeling and Rozitis, 2004, von Tscharner, 2002). According to Hodson-Tole (2009), principal components are a powerful tool to discriminate the fine details of spectral shape that occur when the motor unit recruitment patterns are varied.

**Experimental Design (PhD project aim 2 and 3)**

Due to the tremendous efforts in performing a field study in alpine skiing, one large on snow PhD project using recreational alpine skiers was proposed. The aim of the project was to
create a study design where muscle activity (EMG) data from enough subjects, enough turns per subjects, in different circumstances (e.g. slope inclinations) and in none fatigued versus fatigued condition could be collected.

For the planning of the fatigue part of the project it was considered that recreational alpine skiing reaches a state of fatigue where physiological changes occur yet the activity can still be sustained. Those physiological processes are described for alpine skiing with several approaches and methods (Scheiber et al., 2009, Seifert et al., 2005, Turnbull et al., 2009, Tesch et al., 1978). Consequently, an essential part of the current study design was also to measure those physiological changes for an estimation how this current protocol fits within the skiing sport science literature. In addition those physiological measures can have a significant improvement in the way muscle activity measures from surface EMG can be interpreted since they are directly related to physiological processes. An increase in metabolites such as lactates decreases for example the muscle unit action potentials conduction velocity, and hence, the EMG frequency spectrum shifts to lower frequencies.

Furthermore it was expected, that muscle performance would decrease during a skiing session. This aspect was to the author’s knowledge until now only investigated for an overall skiing week in recreational skiing (Strojnik et al., 2001). But there are no data available how muscle performance is influenced from beginning to the end of a common recreational skiing session. Therefore, the current study design also included this aspect by performing additionally muscle performance tests in the form of isometric strength tests pre and post skiing.

**Approach to the problem for the current experiment:** Table 6 serves a complete outline of the experimental procedure for each subject. Subjects arrived the night before testing and slept in a hotel at the resort. At the hotel a test room for the Isometric strength performance tests and all EMG preparation was available. Directly after arrival subjects were given instructions for the isometric strength tests and a short training session was performed to get used to those tests. On the day of testing each subject consumed a standardized breakfast to be sure that nutrition would not be a primary influence on physiological measures (e.g. no coffee was allowed to drink). Thereafter, EMG preparation took place followed by a standardized 15 minute warm-up on a cycle ergometer and two warm-up runs on the ski slope. At this point the subject preparation phase was finished and the PRE skiing measures started. This phase was divided into indoor isometric strength determination and two measurement runs on the slope (Run 1 and Run 2). Then the skiers had to execute 20 runs (“Sub maximal Skiing Session” Run 3 – Run 22) on the slope where no biomechanical data collection took place.
<table>
<thead>
<tr>
<th>When and where</th>
<th>Task</th>
<th>EMG and KA measures</th>
<th>Other measures</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Evening before Training session</strong></td>
<td>Hotel</td>
<td>Isometric Fmax determination</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Isometric endurance test</td>
<td></td>
</tr>
<tr>
<td><strong>Preparation</strong></td>
<td>Hotel (~90min)</td>
<td>Standardized breakfast</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>EMG preparation</td>
<td>CK, Cortisol (rest conditions)</td>
</tr>
<tr>
<td></td>
<td>Slope (~40min)</td>
<td>Warm up session (20min cycling, two warm up runs on the slope)</td>
<td>HR &amp; RT</td>
</tr>
<tr>
<td><strong>PRE skiing</strong></td>
<td>Hotel (30min)</td>
<td>Goniometer calibration, MVC determination of BF</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Isometric F&lt;sub&gt;max&lt;/sub&gt; determination and EMG MVC determination</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Isometric endurance test (45% to 50% of the F&lt;sub&gt;max&lt;/sub&gt; until exhaustion)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Slope (~30min)</td>
<td>Run 1: measurement run on the slope</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Run 2: measurement run on the slope</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Slope (~30min)</td>
<td>Run 3 to Run 11</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Run 12</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Run 23: measurement run on the slope</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Run 24: measurement run on the slope</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Sub maximal Skiing Session</strong></td>
<td>Empty Bladder</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Run13 to 22</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>POST skiing</strong></td>
<td>Hotel (~30min)</td>
<td>Isometric F&lt;sub&gt;max&lt;/sub&gt; determination and EMG MVC determination</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Isometric endurance test (45% to 50% of the F&lt;sub&gt;max&lt;/sub&gt; until exhaustion)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Goniometer calibration, MVC determination of BF</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hotel (~30min)</td>
<td>Creatin Kinase (3 Hours later)</td>
<td>CK</td>
</tr>
</tbody>
</table>

Table 6: Experimental Setup Overview - General Protocol for one subject
(only physiological data after Run12). Finally skiers had to carry out the POST skiing measures on the slope (Run 23 and Run 24) followed by the isometric strength tests. The skiing session lasted about three hours in which the total skiing time was about 45 minutes.

**Subjects**

*Approach to the problem for the current experiment:* Ten healthy female (22.7 yr ± 4.0 s.d.) subjects provided informed consent to participate in this study. To get a homogenous sample, subjects were selected according to their skiing ability and amount of skiing days per year. All subjects were university sport science students who were physically active but not engaged in competitive training. The recruitment was based on their marks for the practical part of the University skiing course (including criteria: mark 2 or 3). Furthermore, an including criteria was that subjects had performed between 10 and 20 skiing days during the season prior to the start of the experiment. Hence, subjects can be defined as intermediate level skiers based on the Austrian Ski Teaching Concept (Woerndle, 2007). Intermediate level skiers are able to perform short and long radii turns on prepared terrains. In flat terrain, intermediate skiers are able to execute carved turns, but perform mostly skidded turns on steep terrain. All subjects were instructed to refrain from intensive exercise four days before skiing and from mild exercise the day before skiing. Due to logistical reasons the group of 10 skiers was divided into three groups which were tested on different days (Table 7). The timing of each subject’s protocol was strictly standardized from waking to the beginning of testing and further on throughout the day.

<table>
<thead>
<tr>
<th>Day 1</th>
<th>Day 2</th>
<th>Day 3</th>
<th>Standardized Breakfast</th>
<th>Start standardized warm up</th>
</tr>
</thead>
<tbody>
<tr>
<td>26.02.2005</td>
<td>28.02.2005</td>
<td>02.03.2005</td>
<td>Sub7</td>
<td>06:30</td>
</tr>
<tr>
<td>Sub1</td>
<td>Sub4</td>
<td>Sub7</td>
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<td>08:00</td>
</tr>
<tr>
<td>Sub2</td>
<td>Sub5</td>
<td>Sub8</td>
<td>07:15</td>
<td>08:45</td>
</tr>
<tr>
<td>Sub3</td>
<td>Sub6</td>
<td>Sub9</td>
<td>08:00</td>
<td>09:30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sub10</td>
<td>08:45</td>
<td>10:15</td>
</tr>
</tbody>
</table>

*Table 7: Schedule line for all subjects*

Subjects were not allowed to use their own skis. Due to the fact that the slope for on snow testing was standardized skis had to be standardized too. Skis were standardized according to body size and consisted of 150 or 160 cm recreational slalom skis (Atomic, Inc. Altenmarkt, Austria). Those skis were chosen since they fit best for the combination of skier’s level, and
the slope skiers had to ski. Subjects were familiar with the test skis because prior to the experiment they were allowed to use them for a private skiing session.

**Slope**

<table>
<thead>
<tr>
<th>flat</th>
<th>steep</th>
<th>middle</th>
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</thead>
<tbody>
<tr>
<td>13°</td>
<td>29°</td>
<td>21°</td>
</tr>
<tr>
<td>ø 28T</td>
<td>ø 10T</td>
<td>ø 22T</td>
</tr>
<tr>
<td>ø 14dT</td>
<td>ø 5dT</td>
<td>ø 11dT</td>
</tr>
</tbody>
</table>

**Approach to the problem for the current experiment:** Data collection occurred at Hinterreit Ski Area in Maria Alm, Austria during the month of March. This Ski area was chosen since all slopes are served by snow making machines to ensure a consistent snow base. The area is also known for well groomed ski terrain and the slopes are primarily orientated with a northern exposure. Hence the change of environmental temperature due to the daily fluctuation is less pronounced which serves for maintaining better snow quality, but also more accurate EMG data (temperature effect on EMG frequency domain). Furthermore the ski area provides a slope where skiers are confronted with three distinct pitch changes, 21°, 29°, and 13°. Therefore, it was possible to investigate muscle activity also in different inclinations which represents the different skiing situations according the aims of the project. Subjects performed an average of 22 turns on the middle pitch (21°), 10 turns on the steep pitch (29°), and 28 turns on the flat section (13°). Total elevation change for the run was 300 m vertical elevation with the bottom of the run at 890 m above sea level. Total length was 951 m. An average run time took about 100 sec to complete. This run is classified as an intermediate level run. Intermediate level runs are defined as moderate difficulty, moderate length, and a moderate level of risk. To control the length of turns and distance skied across the fall-line, subjects had to ski through a standardized corridor. This methodological approach is an appropriate mix between an absolute standardized course with gates (which is not typical for recreational skiing) and a non standardized free skiing session (which would have been too hard to analyze due to intra and inter subject variations).
Standardizing the load throughout Skiing – Heart rate and run time monitoring

Approach to the problem for the current experiment: Although subjects could ski as they preferred, they were instructed to maintain similar finishing times and HR’s for their individual runs to ensure a standardized load throughout their skiing. To reach this goal, verbal feedback on HR and finishing time was provided to each skier at the end of each run. Before the start of each run, subjects signalled “ready to start” via radio to a person on the test team. The test team then gave the subject the start sign and started the run time (RT) measurement. Upon reaching the finishing line, RT was determined and together with HR recorded on the subject’s score sheet. Both parameters were than given as feedback to the subject together with an instruction for the next run if the load was not on a similar level as in the previous runs. The procedure of standardized load was necessary, to force subjects not to change their way of skiing with e. g. impending fatigue.

(Surface) EMG and Knee Angle Data Acquisition

Approach to the problem for the current experiment: The skin preparation procedure, sensor placement procedure and recommendations for recording was based on the SENIAM guidelines (Hermens et al., 1999, Hermens et al., 2000) and a review by de Luca (De Luca,
The only exception was the placement of the reference electrode. This electrode could not be placed according the SENIAM recommendations (on or around the ankle or the spinous process of C7) because of wearing ski boots and a backpack for the measurement devices. Hence the ground electrode was placed on the patella. Data acquisition took place unilaterally on the right leg. Myoelectric activity was measured from VL, VM and RF muscles using round bipolar surface electrodes (Ag/AgCl; 10mm diameter, 22mm spacing). The EMGs were amplified at the source (bandwidth 10-500Hz, 3dB; Biovision, Wehrheim Germany) and recorded at 2000Hz (Daqcard-700, National Instruments, Austin, TX, USA; iPAQ H3800, Compaq, Houston, TX, USA). Simultaneously, a goniometer mounted on the knee joint measured the occurring knee angle (note that 180° is defined as full extension). The knee angle and myoelectric activity were recorded for the entire four measurement runs (two PREskiing / two POSTskiing).

For complete data analysis, please refer to the previous chapter addressing principle of time frequency analysis via Wavelets and to the two peer review papers of this PhD project where the applied methods are explained in more detail.

*Physiological Measures Blood Lactate, Salivary Cortisol, Creatine Kinase*

**General Information:** In several physiological and biomechanical investigations it is common to collect blood lactate (LA), creatine kinase (CK) and cortisol to assess the acute and overall stress levels of an activity. For alpine skiing Scheiber et al (2009) recently reported that recreational skiing results in a LA of about 2 mmol/L. These data support previously reported average blood LA of of 2.7 mmol/L in younger (18-45 yr old) recreational skiers following 3 hours of self-paced skiing (Seifert et al., 2005). The combined effects of high forces, ischemia, and hypoxia lead to increased muscle stress during skiing as noted by the increase in CK. Seifert et al. (2005) noted a 93% increase in CK levels in recreational skiers following 3 hours of self-paced skiing. Consequently, it makes sense to use parameters which were
already investigated again, to have the possibility to discuss the results of the actual study in relation to previously published work.

Approach to the problem for the current experiment: Salivary and earlobe blood samples were collected after breakfast, following the second, 12th, and immediately after the 24th run. The 20 μL blood samples were analyzed for LA (Biosen 5140, EKF-Diagnostic GmbH, Magdeburg, Germany). An additional blood sample was collected after breakfast and 3 hrs post skiing and analyzed by reflectance photometry at 25°C for CK (Reflotron). The blood was stored in a glass capillary at cold but not freezing temperatures until analysis took place. Within 6 hours after the blood was collected, all samples were analyzed in the laboratory. Salivary sample were analyzed for cortisol (Diagnostic Products, Inc.) after having been frozen and transported by Dr. J. Seifert to a laboratory at St. Cloud State University, USA.

Isometric strength tests

<table>
<thead>
<tr>
<th>Used abbreviations:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Test:</td>
</tr>
<tr>
<td>Peak Force…………… F&lt;sub&gt;max&lt;/sub&gt;</td>
</tr>
<tr>
<td>Isometric endurance test:</td>
</tr>
<tr>
<td>Time till exhaustion………ET</td>
</tr>
</tbody>
</table>

General Information (see Maud and Foster, 2006): A common method of assessing muscle performance is isometric testing, in which the length of the active muscle remains constant. Isometric testing removes variations in the velocity of movement, because all tests are performed at 0°s<sup>-1</sup>. Isometric testing involves using a force transducer and an immovable resistance. In this case, the force plate measured ground reaction force while the individual exerted isometric force at a predetermined angle. The precise joint angle of the individual can normally be adjusted infinitely and is then measured with a goniometer. Although peak force assessment is often the primary purpose for isometric testing, other data can be generated. Fatigue tests for example are commonly used with isometric devices to assess local muscular endurance. Those isometric performance tests can be quantified in several ways with fatigue being defined as the time interval for which the individual can maintain a certain percentage of the peak force.

Approach to the problem in the current experiment: Peak isometric force was measured with a force plate mounted on an upright, stationary seat. The right leg was used for testing with a
knee angle of 100°. Three leg press attempts were conducted to achieve peak force with the highest value used for statistical analysis. The ramping protocol was such that in 3 s subjects would gradually reach and maintain peak force. A rest interval of 12 s was provided between attempts. The isometric endurance test was completed five minutes after the peak force test was completed. The endurance test was performed at 45-50% of the pre-skiing maximal isometric force with a knee angle of 100°. The test was terminated when sustained force decreased below the 45% of peak force for a total of 1.5 seconds. Verbal encouragement was not provided to the subjects during these tests. Visual feedback on force output was made available to the subjects; however, they did not receive information on elapsed time during the endurance test. The tests were accomplished during the PRE skiing and POST skiing session as shown in Table 6.

Data Analysis

Data recorded throughout the whole experimental setup were divided into separate analysis parts, to answer different scientific questions:

**Part 1:** Application of EMG Wavelet Technique: Functional aspects of the knee extensor muscle group in recreational skiers

**Part 2:** Application of EMG Wavelet Technique – Muscular fatigue in recreational skiing

Table 6 serves as an overview for measures of each part of the PhD project. The label “1” represents measures considered for Part 1 and “2” measures considered for Part 2. Those two parts represent the main aims of the PhD Project. The corresponding work on these aims is reported within the following Results chapter of the current thesis. Due to the fact that the protocol was also applicable to answer a physiological question related to fatigue in recreational skiers, a third part was created as a so-called side project within this theses:

**Part 3:** Side project - Physiology

The purpose of this part of the project was to investigate the relationship and predictors of common fatigue indices during downhill skiing, and is presented as third peer reviewed paper within the following Results chapter of the current thesis.
Results / Publications for the cumulative PhD

Part 1: Application of EMG Wavelet Technique: Functional aspects of the knee extensor muscle group in recreational skiers

Preliminary paper

Peer reviewed Article

Part 2: Application of EMG Wavelet Technique - Fatigue in recreational skiing

Preliminary paper


Peer reviewed Article

Part 3: Side project - Physiology

EMG signal processing by wavelet transformation – applicability to alpine skiing

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2 School of Kinesiology, Simon Fraser University, Canada
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1 Introduction

Surface electromyography (EMG) is often used to evaluate muscle activity during movement. Review of EMG literature during alpine skiing indicates that amplitude and timing pattern of muscle activity have been analyzed along with the relative activity of different muscles (e.g. Berg et al 1995, knee extensors). Due to the involvement of different muscle fibre types (slow and fast twitch fibres) and their different motor unit action potentials, the frequency of an EMG signal contains additional information about muscle fibre activation. When a muscle is active, the fast fibres can generate higher frequencies within the signal than slow fibres (Wakeling, 2008).

The frequency content of a signal can be analyzed by computing a power spectrum. This additional information helps to describe the muscle recruitment in a more in-depth manner. The mean or median frequency of the power spectrum, calculated by a Fourier transformation, is e.g. an accepted index for monitoring fatigue in static contractions (MacIsaac et al, 2000). The disadvantage of this median power frequency (MPF) technique is the necessity of a stationary signal behaviour over a substantial time span (200ms or longer; von Tscharner, 2002). This limits the analysis for any non-stationary signals which are normally observed during dynamic exercises, like alpine skiing.

Nevertheless, analysis of the EMG frequency content has been previously performed in alpine skiing by calculating the median power frequency (Kröll et al, 2005). During alpine skiing, one can observe a quasi stationary signal from the outside leg during the steering phase within a turn. During this phase of the turn, there is a high level of quadriceps activation while the knee angle and ground reaction forces are stable. Therefore, the assumption of a quasi static
EMG signal processing by wavelet transformation – applicability to alpine skiing

contraction (stationary signal) was made. The purpose of the 2005 study was to determine changes in the MPF on an isometric endurance test and/or during skiing caused by a fatiguing skiing session. Fatigue was induced in 10 recreational skiers by skiing 20 runs on a slope with 300m elevation. During skiing, the quasi static part of the first five turns and the last five turns of the run were analysed to determine the shift of the MPF within a run. Prior to the fatiguing skiing session the MPF showed no differences at beginning of the run compared to the end. After fatiguing, strong tendencies for a shift in MPF were observed. A downward shift of the MPF for the m. vastus lateralis (VL) was observed, yet m. vastus medialis (VM) responded in an opposite fashion with a tendency to move towards higher frequencies. Fatigue is typically associated with a reduction in frequencies. Increases in EMG frequencies during sustained exercise have previously been suggested to result from altered motor unit recruitment (Wakeling et al. 2001) and it is possible that this also occurs for skiing, at least for the VM. The results could indicate some kind of a compensation strategy as a result of muscle specific fatigue (e.g. fatigued VL versus not fatigued VM).

As mentioned, the disadvantage of the MPF method is the collapse in the temporal aspects of the signal (von Tscharner, 2002). In the case of alpine skiing, the whole movement was reduced to 500ms of activity from the outside leg during a turn. This means that some functional phases are ignored (inside leg, edge changing, loading and unloading characteristics of the ski) and there is only partial applicability of the method for complex muscle recruitment studies. Developments in wavelet analyses for EMG permit the signal intensities to be simultaneously resolved in time and frequency, with time resolutions in the order of 20 ms (von Tscharner, 2000). The resulting intensities are a close approximation of the signal power contained within a given frequency band at each time point. This presents the possibility to visualize the EMG intensity pattern of a movement in time frequency space during each cycle of a movement as it has been previously demonstrated for running and cycling (von Tscharner 2002, Wakeling 2004).

Due to the primarily cyclical movement patterns in alpine skiing, it is hypothesized that the methods used to analyze running and cycling are applicable to
the complex activity alpine skiing. There appears to be potential for a more in-depth analysis of muscle activity during alpine skiing, by the use of wavelets.

Thus, the aim of the current project was to perform a time-frequency analysis of the EMG intensities during alpine skiing using wavelet transformation. Functional differences in EMG time and frequency patterns within the quadriceps muscles where analyzed. The current topic was chosen because of a previous study by Berg et al (1995) who reported differences within the quadriceps muscles with respect to only EMG amplitudes.

2 Methods

Ten female recreational skiers (selected by their skiing ability) performed two runs through a standardized corridor on a slope with 300m elevation and three different sections of inclination. In the current paper, only the results of the middle inclination (21°) were considered. On average, 11 double turns (one right plus one left turn) per run were performed in this section.

Knee angle and muscle activity of m. vastus lateralis (VL) & m. rectus femoris (RF) were measured by a goniometer and bipolar surface EMG sensors during the runs, respectively. Data were acquired unilaterally from the right leg. The signals were recorded at 2000Hz with a mobile EMG measurement device (Biovision, Werheim, Germany) carried in a backpack.

For each run all double turns of all subjects in the considered inclination were analyzed. The knee angle and raw EMG were used to determine the start and end of each double turn [1st turn right leg = inside leg (IL); 2nd turn right leg = outside leg (OL)]. The start and end points reflect, more or less, the point of edge changing. Each double turn was further divided into 10 equal time windows (TW). Each of these windows will reflect the mean of the EMG information for this time period. It is again a reduction of data in time space, but it seems to be an ideal compromise between holding time information and giving the possibility to summarize the information for further statistical calculations (cf. Berg et al 1995).

The entire recorded EMG signal was resolved with an EMG-specific wavelet transformation into intensities for each point in time calculated for a set of 10
Wavelets (WL) with centre frequencies (CF) between 19.3 and 395.4 Hz (von Tscharner 2000). To identify signal artefacts the data from that double turn were considered noisy and excluded if the EMG intensity at WL1 domain (cf=19.3Hz) was greater than that for the WL2 domain (cf=37.3 Hz; Wakeling 2004). This resulted in a subject reduction from ten to seven.

For all double turns, the mean intensity for each WL and each TW (10 per double turn) was calculated and intra individual normalized to the mean overall signal intensity. To get the representative result for a subject the mean over all turns for each WL-TW-combination was built. To get a representative result for the group the same was done over all subjects.

Descriptive analysis was completed using 3D intensity grid-plots for the overall group and individual skiers. Those plots represent WL1 to WL9 on the vertical axis represented by CF (19Hz to 331Hz) and the time information by TM (1-10) on the horizontal axis. The intensity is represented by the colours, whereas bright means high intensity and dark denotes low intensity. Each plot is internal normalized by the highest value (=white) and the lowest value (=black).

3 Results and Discussion

Overall Group (Fig. 1/A):

The grid plots of the overall group show substantial differences between VL and RF. According the timing of muscle activity, one can observe that both muscles denote a clear phase of inactivity at begin of each double turn (TW1). VL is active throughout the double turn with maximum intensities during TW7-8 where the measured right leg is the OL. In contrast, RF shows a biphasic activity with two clear maxima on IL (TW3) and OL (TW8) and low activity during edge changing from IL to OL (TW5-6). According to the frequency content, one can observe on VL the slightly greater involvement of higher frequencies during OL compared to IL. In contrast, the results of RF clearly indicate a more pronounced involvement of higher frequencies during IL compared to OL.

The finding concerning intensities is in agreement with results from Berg et al (1995) for giant slalom racing.
Due to the fact that current skiing technique has changed to a more bilateral style (Müller et al 2003), one could assume that there would be higher activity.
during IL. Although, our skiers performed a modern recreational carving technique, the predominant unilateral use (OL) of the one joint knee extensor VL seems to be given. The contrasting biphasic patterns of RF suggest that this two joint muscle works as knee extensor during OL, but also as a hip flexor and/or knee extensor during IL. The speculative functional extension of RF as knee extensor on IL, compared to the single hip flexor function described by Berg et al. (1995) is based on changed skiing technique. We assume, that there is currently a situation dependent loading (RF as knee extensor) and unloading (RF as hip flexor) necessary which is reflected in the EMG activity.

The difference in frequency content between RF and VL provides additional information on the functional characteristics of those muscles during skiing. It is possible that RF recruits more fast fibres during IL (higher frequencies) compared to more slow fibres during OL. With the already mentioned functional skiing technique aspects, this would mean that RF recruitment, and specifically the fast components, is an important steering factor during IL. The ability to recruit fast RF fibres over a substantial time (hundreds of IL turns during a day) seems to be a crucial aspect in alpine skiing. Alpine skiers could thereby obtain an adequate bilateral loaded skiing technique (IL=knee extension), but also be able to avoid too high loading of the IL (hip flexion). A potential consequence of high loading of the IL is a fall due to over edging. The results obtained from RF may have specific and practical, implications for conditioning programs to both recreational and racing alpine skiers.

Individual result of two subjects (Fig. 1/B; Fig 1/C):

Although the focus of the present study was to identify general patterns in muscle activity and muscle use during recreational skiing, not to our surprise we observed considerable inter-individual variation. Subject C for example, corresponded in large parts with the overall group result. Otherwise subject B shows fundamental differences in VL (higher IL activity) and RF (IL frequency content similar to OL) compared to the overall group. The individual skier, however, showed highly reproducible patterns along the turns. This leads to the assumption, that this method could also be a useful tool in quantifying individual skiing strategies / techniques (e.g. in alpine ski racing).
4 Summary and further application

Using the wavelet analysis gives the potential to extract conventional intensity and timing information as well as additional information about the frequency content of the signal. The principal differences of the two-joint RF and the one-joint VL were described with greater depth and detail than by the common methods used by Berg in 1995. In conclusion, wavelet analysis can be a powerful tool in describing muscular activity for alpine skiing in a more in depth manner. The present study gives descriptive ideas to the possibility of how this method can be applied in alpine skiing based on an isolated simple situation. Future studies will combine the used method with statistical quantification (e.g. principal component analysis; Wakeling 2004) to answer scientific questions in alpine skiing such as: influence of different "slope inclinations", "prolonged sub-maximal skiing" or "specific conditioning" on muscle recruitment.

References

Quadriceps Muscle Function during Recreational Alpine Skiing

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\textsuperscript{1}Department of Sport Science and Kinesiology, University of Salzburg, AUSTRIA; \textsuperscript{2}Christian Doppler Laboratory “Biomechanics in Skiing,” Salzburg, AUSTRIA; \textsuperscript{3}Department of Biomedical Physiology and Kinesiology, Simon Fraser University, Burnaby, British Columbia, CANADA; and \textsuperscript{4}Movement Science Laboratory, Montana State University, Bozeman, MT

ABSTRACT

KRÖLL, J., J. M. WAKELING, J. G. SEIFERT, and E. MÜLLER. Quadriceps Muscle Function during Recreational Alpine Skiing. Med. Sci. Sports Exerc., Vol. 42, No. 8, pp. 1545–1556, 2010. Purpose: Since the introduction of carving skis, muscle activity has been investigated primarily on expert-level skiers with respect to EMG intensities. The three-part aim of this recreational skiing study was to analyze functional differences within the quadriceps muscle, to analyze the topographical influence, and to apply a time–frequency analysis of the EMG intensities using wavelets. Methods: Seven female subjects performed two runs through a standardized corridor on a slope with different inclinations (13°, 29°, and 21°). Knee angle and EMG of vastus lateralis (VL) and rectus femoris (RF) of the right leg were measured during the runs. The recorded EMG signal was resolved with a set of 10 wavelets (11–432 Hz) into a time–frequency space. Subsequently, the EMG intensity and mean frequency (MF) were calculated for different time windows (inside leg; outside leg). Result: For RF, a significantly higher MF (+15.5%, $P = 0.009$) but similar EMG intensities were detected in the inside leg compared with the outside leg. For VL, the MF ($-9.6\%, P = 0.053$) and EMG intensities ($-54.3\%, P = 0.010$) were lower in the inside leg compared with the outside leg. Both muscles responded with higher EMG intensities on increasing slope inclination (VL = 90.8\%, $P = 0.022$; RF = 115\%, $P = 0.01$). MF is not directly related to inclination. Conclusions: Contrary to previously suggested coloading of the inside leg while carving, our results do not support this hypothesis for VL. However, the functional demand for RF in the inside leg is very high when skiing recreationally. The ability of a situation-dependent loading (RF as knee extensor) and unloading (RF as hip flexor) of the inside leg seems to be a crucial point with respect to specific fatigue during a skiing day. Key Words: EMG, MUSCLE ACTIVITY, WAVELET ANALYSIS, FREQUENCY, SLOPE INCLINATION

There have been considerable changes in equipment design and movement patterns in alpine skiing during the past decade. One of the most important changes in movement patterns is the increased coloading of the inner leg during the turning phase compared with the previous pattern where there was a predominant loading of the outer leg (19). This change seems to be omnipresent throughout all skill levels (37). A more in-depth understanding of muscle activity during various situations while skiing would provide useful information pertaining to skill acquisition, appropriate movement progression, and physical conditioning for skiers.

Previous research on muscle activity during skiing was published before carving skis were introduced, and all of these reports included competitive or expert-level skiers (1,2,12,19,21,38). One consistent finding of previous works was that there is a high level of effort by the knee extensor muscles during skiing and this activity is dominated by eccentric contractions (2,4). Functional differences were clearly observed within the knee extensor muscles. The substantially higher vastii EMG activity in the outside leg compared with that in the inside leg confirms the generally accepted notion of a predominantly unilateral use of the knee extensors during alpine skiing. The contrasting biphasic EMG pattern of the rectus femoris (RF) muscle suggests that this two-joint muscle serves a dual purpose, both as a knee extensor during the outside ski phase (outside leg) and as a hip flexor during the inside ski phase (inside leg) (2). Because of the equipment used today and the suggested coloading of the inside leg while using this equipment (19), we hypothesize that the function within the main knee extensor muscles has changed. This fact, and the lack of information on recreational skiers, led us to the first aim of the present study:

1. To investigate functional differences of the one-joint vastus lateralis (VL) and two-joint RF knee extensor muscle in recreational skiers.

Those muscles were chosen because RF is a two-joint muscle and VL is a one-joint muscle with the primary role
of knee extension (27). Comparative studies between VL and vastus medialis have shown that they are activated simultaneously when the knee is flexed from 40° to 80°. The vastus medialis seems to become most pronounced at full extension (0°–40° flexion), with the function a dynamic medial patellar stabilizer of the knee (27). Typical knee angle flexion range in alpine skiing is from 60° to 90°. For this reason, not surprisingly, similar results for VL and vastus medialis were reported during alpine skiing (2,12).

Because of this similarity, only VL was considered as one-joint knee extensor.

Alpine skiers have to deal with the influence of the topographical environment. This influence can also be intentionally used to control the physiological load during a skiing session (23). As a consequence, the choice of slope inclination can be an important factor in safety and comfort issues. Clarys et al. (4) investigated the influence of slope inclination on muscle activity during skiing. Expert-level skiers skied through a giant slalom course while several leg muscles were analyzed with EMG. The results indicated that the muscular activity increased with increasing slope angle. It should be noted that data were presented as grouped over all muscles because each muscle analyzed separately did not allow for the detection of a possible topographical influence on muscle activity. Nevertheless, Clarys et al. (4) suggested that the inclination of the slope is an important discriminating factor for muscle activity. Thus, the second aim of the study is as follows:

2. To investigate the influence of different slope inclinations on the functional properties of VL and RF in recreational skiing.

Up to now, amplitude and the timing pattern of muscle activation have been the primary EMG variables studied in alpine skiing. Because of the involvement of different muscle fiber types (slow-twitch and fast-twitch fibers) and their different motor action potentials, the frequency of an EMG signal contains additional information about muscle fiber activation. When a muscle is active, the faster fibers can generate higher frequencies than the slow fibers within the given signal (33).

The mean frequency (MF) of the power spectrum, calculated by a Fourier transformation, was used by Kröll et al. (14,15) and Ushiyama et al. (28) to evaluate fatigue during alpine skiing. The disadvantage of this method is the collapse in the temporal aspects of the signal (31). Kröll et al. (15) had collapsed the whole movement from 1200 ms to 500 ms of activity from the outside leg during a turn. This means that some functional phases are ignored (inside leg, edge changing, loading, and unloading characteristics of the ski) and only partial applicability of the method for complex muscle recruitment is given.

Developments in wavelet analyses for EMG permit the visualization of the EMG intensity pattern of a movement in the time–frequency space during each cycle of a movement. This method has been previously demonstrated for running and cycling (31,32,36). Because of the cyclical movement patterns in the complex activity of alpine skiing, this wavelet method is also appropriate for alpine skiing. Thus, the third aim of the study is as follows:

3. To create a new, more in-depth, method for muscle activity studies in alpine skiing (aims 1 and 2 of the current study) by performing a time–frequency analysis of the EMG intensities using wavelet transformation.

METHODS

Subjects

Seven healthy female subjects (22.7 ± 4.0 yr) provided informed consent to participate in this study following institutional review board approval. All subjects were healthy, university sport science students who were physically active but not engaged in competitive athletic training. To get a homogenous sample, subjects were selected according to their skiing ability and amount of skiing days per year. All subjects were of the intermediate level on the basis of the Austrian Ski Teaching Concept (37). Intermediate-level skiers are able to perform short- and long-radii turns on prepared terrains. On flat terrain, intermediate-level skiers are able to execute carved turns but perform mostly skid turns on steep terrain.

Experimental Design and Slope Intervention

Data collection took place at Hinterreit Ski Area in Maria Alm, Austria, during the month of March. All subjects followed a standardized warm-up by completing a 15-min warm-up on a cycle ergometer and two warm-up runs on the ski slope. Skiers were then instructed to perform two measurement runs. To control the length of turns and distance skied across the fall line, subjects skied through a standardized course.

FIGURE 1—Slope geometry, average amount of turns and double turns per subject and run in the different inclinations.

<table>
<thead>
<tr>
<th>Inclination</th>
<th>middle</th>
<th>steep</th>
<th>flat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclination</td>
<td>21°</td>
<td>29°</td>
<td>13°</td>
</tr>
<tr>
<td>Turns</td>
<td>ø 22T</td>
<td>ø 10T</td>
<td>ø 28T</td>
</tr>
<tr>
<td>Double Turns</td>
<td>ø 11DT</td>
<td>ø 5DT</td>
<td>ø 14DT</td>
</tr>
</tbody>
</table>

Start

230m 81m 86m 118m 541m

Finish

| Start | 230m 81m 86m 118m 541m | Finish |

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corridor on a groomed ski terrain. The total elevation change for the run is 300 m vertical elevation with the bottom of the run at 890 m above sea level. Skis were standardized according to body size and consisted of 150- or 160-cm recreational slalom skis (Atomic, Inc., Altenmarkt, Austria). Within each run, there were three pitch changes, namely, 21°, 29°, and 13°. Subjects performed an average of 22 turns on the 21° segment, 10 turns on the steep segment, and 28 turns on the flat segment (Fig. 1).

**EMG and Kinematics Measurement**

Data acquisition took place unilaterally on the right leg. Myoelectric activity was measured from the VL and RF muscles using round bipolar surface electrodes (Ag/AgCl;
10-mm diameter, 22-mm spacing). The sensor placement procedure is based on the SENIAM recommendations (10,11). The reference electrode could not be placed according the SENIAM recommendations (10) (on or around the ankle or the spinous process of C7) because of wearing ski boots and a backpack for the measurement devices. Hence, the ground electrode was placed on the fibular head, above the ski boot. The EMG were amplified at the source (bandwidth of 10–500 Hz, 3 dB; Biovision, Wehrheim, Germany) and recorded at 2000 Hz (Daqcard-700 (National Instruments, Austin, TX) and iPAQ H3800 (Compaq, Houston, TX)). Simultaneously, a goniometer mounted on the knee joint measured the occurring knee angle (note that 180° is defined as full extension). The knee angle and myoelectric activity were recorded for the whole two measurement runs.

Wavelet Analysis of EMG during Alpine Skiing

The principal analysis method of the alpine skiing EMG signal is based on earlier studies by Wakeling in running (32) and cycling (36). The entire EMG signal (Fig. 2A) was resolved with an EMG-specific wavelet transformation. The intensity was calculated using a filter bank of wavelets following von Tscharner (30). Each wavelet has a frequency band (Table 1), and the time-varying intensity is calculated for this band. For each instant in time, the EMG is thus represented by its intensity at a range of frequency bands, and this is termed the intensity spectrum.

Table 1. Parameters of the used wavelets (identical with von Tscharner [30]).

<table>
<thead>
<tr>
<th>Wavelet No.</th>
<th>Center Frequency (Hz)</th>
<th>Bandwidth (Hz)</th>
<th>Time Resolution (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>19.29</td>
<td>15.63</td>
<td>59.0</td>
</tr>
<tr>
<td>2</td>
<td>37.71</td>
<td>21.48</td>
<td>40.5</td>
</tr>
<tr>
<td>3</td>
<td>62.09</td>
<td>27.34</td>
<td>31.5</td>
</tr>
<tr>
<td>4</td>
<td>92.36</td>
<td>35.16</td>
<td>26.0</td>
</tr>
<tr>
<td>5</td>
<td>128.48</td>
<td>46.55</td>
<td>19.5</td>
</tr>
<tr>
<td>6</td>
<td>170.39</td>
<td>52.73</td>
<td>16.5</td>
</tr>
<tr>
<td>7</td>
<td>218.08</td>
<td>58.59</td>
<td>15.0</td>
</tr>
<tr>
<td>8</td>
<td>271.50</td>
<td>66.41</td>
<td>13.5</td>
</tr>
<tr>
<td>9</td>
<td>330.63</td>
<td>72.27</td>
<td>12.0</td>
</tr>
<tr>
<td>10</td>
<td>395.46</td>
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</table>

Elimination of artifacts. Wavelet 1 covered a frequency band of 11–27 Hz, which is typically associated with ski-specific movement artifacts caused by uncontrolled vibrations (7). If the intensity from a certain time frame resolved by this wavelet was greater than the maximum intensity resolved by the higher wavelets, then the data from that time frame were considered noisy and that turn was

Myoelectric (EMG) intensity and MF of a spectrum. The total intensity at each time frame was calculated as the sum of the intensities within each spectrum (across wavelets 1–10, corresponding to frequency bands 11–432 Hz), and this is termed the EMG intensity (Figs. 2E and F). EMG intensities at each of the considered time frames (inside leg, outside leg, time windows 1–10) were normalized to the mean EMG intensity from all overall double turns on the flat inclination for each subject and muscle.

The MF at each time frame was defined as the sum of the intensity–frequency product over wavelet domains 1–10 divided by the sum of the intensities, using the following equation (34):

\[
MF = \left( \frac{\sum_{\text{wavelet}1} \left( \text{intensity} \times \text{center frequency} \right)}{\sum_{\text{wavelet}10} \text{intensity}} \right) \]

FIGURE 3—Knee angle of the group (n = 7, right leg) expressed for a full movement cycle (double turn) including inside leg (first turn, right turn) and outside leg (second turn, left turn). Above: Average knee angle values (±SE) over the whole inside leg versus the whole outside leg in the different inclinations (gray = medium, dark gray = steep, bright gray = flat). Below: Trace of average knee angle values (±SE) for 10 time windows in the different inclinations (square = medium, triangles = steep, circles = flat).
not analyzed further (32). If more than 40% of the overall double turns for a given inclination were identified as noisy, then that subject was eliminated from further analysis. This elimination led to a reduction in subjects analyzed from 10 to 7.

Statistics

For each double turn, the EMG intensity and the MF for each of the different time frames were calculated as described above. To get representative results for a subject from both parameters (EMG intensity and MF), the mean over all turns in a certain inclination was calculated. To get a representative result for the group, the same was done over all subjects.

The significance of the muscle response on the turning side (functional aspect of the two-joint vs the one-joint muscle) and slope steepness were tested with an ANOVA \((2_{\text{inside leg/outside leg}} \times 3_{\text{inclination}})\) ANOVA for the variables EMG intensity and MF. The same was done for knee angle. In case of statistical significance, additional post hoc testing was performed using the Bonferroni method. Descriptive analysis over the 10 time windows was completed to show the response for the overall group and individual skiers. All data are presented as mean ± SEM \((n = 7)\). SD was used for the individual results due to the different amount of turns in different inclinations. Statistical tests were deemed significant at \(\alpha = 0.05\).

RESULTS

Knee Angle

Average knee angle of the inside leg \((94° ± 5°)\) was significantly lower \((P < 0.001, \eta_p = 0.901)\) compared with that of the outside leg \((114° ± 4°)\). The influence of the slope inclination was not significant (Fig. 3A).

The time course of knee angle is shown in Figure 3B. During the first part of the double turn, where the right leg is the inside leg (time windows 1–5), the knee angle is continuously reduced to a minimum of approximately 85° at time window 4. The following two time windows represent the phase of edge changing where the right leg is becoming the outside leg. During this phase, an extension of the leg by approximately 30° is observed. In the following phase, the right leg is the outside leg, and the knee angle seems to be relatively constant at approximately 115°. The knee angle coincided among the different inclinations for time windows 2–4 and time windows 6–10 with a maximum difference <6°. Time windows 1 and 5 depict maximum differences <10°. Within a run, each skier showed small variations concerning minimum and maximum knee angles.

EMG Intensity and MF

Figure 4 contains an overview of the EMG data used to analyze the functional difference of VL and RF (inside leg vs outside leg) and to assess the influence of the slope inclination.
inclination. The VL showed significantly lower EMG intensity values ($P = 0.010$, $\eta_p = 0.762$) in the inside leg (0.91 ± 0.11) compared with those of the outside leg (1.99 ± 0.24; Fig. 4A). Contrary to the VL, the EMG intensity effects between the inside leg and the outside leg for RF (Fig. 4B) were minor and in the opposite direction (1.66 ± 0.26 vs 1.38 ± 0.30, $\eta_p = 0.070$).

Accordingly, the MF in Figures 4C and D reflect a different behavior of VL and RF recruitment between the inside leg and the outside leg. The VL demonstrated a strong tendency for lower MF in the inside leg (68.8 ± 4.8 Hz, $P = 0.053$, $\eta_p = 0.561$) compared with the outside leg (76.1 ± 4.8 Hz). On the other hand, it was observed that RF showed significantly higher MF for the inside leg (84.2 ± 4.3 Hz, $P = 0.009$, $\eta_p = 0.705$) compared with the outside leg (72.9 ± 5.6 Hz).

A similar effect of the slope inclination on muscle recruitment was observed in both muscles. Both muscles responded with higher EMG intensities on increasing slope inclination. The VL EMG intensities are shown in Figure 4A (middle = 1.45 ± 0.21, steep = 1.87 ± 0.19, flat = 0.98 ± 0.02, $P = 0.022$, $\eta_p = 0.853$), and RF EMG intensities are shown in Figure 4B (middle = 1.45 ± 0.27, steep = 2.13 ± 0.35, flat = 0.99 ± 0.01, $P = 0.050$, $\eta_p = 0.670$).

Contrary to the EMG intensities, the frequency content of the EMG signal showed no direct relation with the slope inclination (Figs. 4C and D). Both VL and RF exhibited the highest MF in the first segment (middle inclination: VL = 74.6 ± 4.7 Hz, RF = 79.6 ± 5.0 Hz) and lowest MF in the last segment of the run (flat inclination: VL = 70.6 ± 4.4 Hz, RF = 76.9 ± 4.5). The MF in the middle segment of the run (steep inclination: VL = 72.2 ± 4.6 Hz, RF = 79.1 ± 5.0 Hz) was in between. This observation was significant for VL ($P = 0.001$, $\eta_p = 0.976$) and showed a tendency for RF ($P = 0.096$, $\eta_p = 0.609$). There seems to be a direct relation to the time within a run (first segment > second segment > third segment) but not to the inclination.

Regarding the EMG intensities, significant effects for the inclination × turn side interaction term were observed for both muscles (VL: $P = 0.050$, $\eta_p = 0.776$; RF: $P = 0.006$, $\eta_p = 0.868$). The MF, on the other hand, offered no significant difference in the inclination × turn side interaction.

Figure 5 shows the course of EMG intensities (A, B) and MF (C, D) of the studied muscle from time window 1 to time window 10. Comparing VL and RF differences in timing, EMG intensity and MF can be observed. According to the timing of muscle activity, it can be observed that both muscles demonstrate a clear phase of inactivity at the beginning.
of each double turn (Fig. 5; relative EMG intensities; time window 1). The VL has a plateau-type response in a low level of activity from time window 2 to time window 5 (inside leg). Activity increases to maximum EMG intensities during time windows 7–8 when the right leg is the outside leg. Activity then decreases afterward (Fig. 5A). In contrast, RF shows a biphasic activity pattern with two clear maximal periods, one from the inside leg (time window 3) and one from the outside leg (time window 8). Low activity patterns occur during edge changing from inside leg to outside leg (time windows 5–6). As described and statistically supported, the VL shows higher MF in the outside leg compared with the inside leg. The course shows a continuous increase in the inside leg (time windows 1–5) followed by a plateau in the outside leg (time windows 6–10; Fig. 5C). In contrast, the result of RF clearly indicates a more pronounced involvement of higher frequencies in the inside leg compared with the outside leg. The course of RF mean frequencies indicates a plateau both in the inside and outside leg (Fig. 5D).

VL shows a substantial influence of slope inclination on the outside leg (time windows 6–10) but only a minor influence on the inside leg (time windows 1–5). The RF exhibited higher EMG intensities for the inside and outside leg in the steep segment compared with the flat segment (Fig. 5B). The course of the MF between steep and flat inclination is nearly parallel throughout time window 1 to time window 10 for both muscles. We observe slightly higher values in the steep inclination compared with those in the flat inclination.

However, in combination with the medium inclination (described above; Figs. 4C and D) and our experimental setup, one can observe a progressive decrease in MF throughout the run, but no direct relation between inclination and MF.

DISCUSSION

Functional Differences of RF and VL

EMG intensity content. The generally accepted notion of a predominantly unilateral use of the one-joint knee extensors during alpine skiing, which was stated by Berg et al. (2), had to be revised with the introduction of the carving skis. Mueller and Schwameder (19) found in their comparative technique analysis between traditional parallel technique and the carving technique that, in a traditional parallel turn, the predominate load is on the outer ski (outside leg), whereas intensive coloading of the inside leg is found in all turning phases with the carving technique. The knee extensors vastus medialis (19) and VL (21) are activated similarly in the inside leg as in the outside leg. Hence, biphasic activation can be observed. Although our subjects were familiar with carving skis and were able to perform a modern recreational carving technique, the muscle activity results corresponded more closely with those of Berg et al. (2) than with the results for carving technique by Mueller and Schwameder (19). A predominant unilateral use of the one-joint knee extensor VL seems to be evident. However, in the flat segment of the run, our subjects showed a tendency of biphasic behavior of VL (Fig. 4A) because time window 6 has lower EMG intensity than time windows 5 and 7. The skiing level of our subjects was defined as intermediate, which means that they are able to execute carved turns on flat terrain but perform mostly skid turns on steep terrain (37). Hence, it can be concluded that it is not the use of shaped skis per se that led to a coloading of the inside leg. Moreover, it was the skier’s individual ability to perform a carved turn in a certain inclination that seems to be a dominant factor.

In contrast to VL, our data demonstrate a clear biphasic behavior on the two-joint RF. This supports previous results before and after the introduction of the carving skis (2,19). However, the mechanisms seem to be different. Berg et al. (2) suggested that RF serves a dual purpose, both as a knee extensor during the outside ski phase (outside leg) and as a hip flexor during the inside ski phase (inside leg). The data of Mueller and Schwameder (19) demonstrated a functional extension of RF as a knee extensor in the inside leg compared with the single hip flexor function described by Berg et al. (2) on the basis of changed skiing technique (coloading aspect). This conclusion is supported by their kinetic parameters. Berg et al. (2) reported higher EMG activity in the outside leg compared with the inside leg, whereas the data of Mueller and Schwameder (19) showed no differences. The data of the present study showed slightly higher values from the inside leg than from the outside leg (Fig. 5B). Therefore, it can be suggested that the demand is very high for RF during the inside leg phase of recreational skiing. We assume that there are currently situation-dependent loading (RF as knee extensor) and unloading (RF as hip flexor) activities necessary, which are reflected in the EMG of the inside leg. From a coordinating point of view, recreational alpine skiers could thereby obtain an adequate bilateral loaded skiing technique when the inside leg begins to extend the knee but also be able to avoid too high loading of the inside leg when flexing the hip. A potential consequence of high loading on the inside leg is a fall due to overedging.

Although the focus of the present study was to identify general patterns in muscle activity during recreational skiing, a considerable range in interindividual variations was observed. Subject Y, for example, showed fundamental differences in VL (Fig. 6C) compared with the overall group (Fig. 5A). A biphasic VL activation was observed, which indicates a coloading of the inside leg for this subject. The results of subject X corresponded for VL (Fig. 6A) in large parts with the overall group (Fig. 5A). However, RF of this subject (Fig. 6B) shows substantial differences in activation compared with the biphasic group result (Fig. 5B).

EMG MF content. The difference in mean frequencies between RF and VL provides additional information on the functional characteristics of those muscles during skiing.
Wakeling et al. (35) reported three main properties of muscle activation, which shape myoelectric frequency spectrum. For each muscle fiber, the motor unit action potential (MUAP) that travels along it has both a characteristic shape and velocity. The shape and conduction velocity of the MUAP also vary between different muscle fibers and, thus, different motor units. There are different mechanisms that can alter the shape and conduction velocity of EMG records, which are primarily fatigue-dependent (35). These mechanisms are not responsible for the observed differences in MF because the factor fatigue has no influence on principal functional aspects. One important non-fatigue-dependent mechanism in altering the signal frequency is the influence of the muscle length. Models of the EMG suggested that the muscle fiber areas (diameters), which increase during shortening a muscle, are the major factor behind the shape and conduction velocity of the MUAP (9). It has been demonstrated that the EMG frequency spectrum shifts to higher frequencies with decreased muscle length (6,20).

To discuss the MF of the EMG signal during alpine skiing with respect to functional differences of VL and RF, it is necessary to estimate changes in muscle length over the double turn (time windows 1–10). In several skiing-related kinematics studies where hip and knee angle were measured simultaneously (1,2,18), the minimum and maximum angles coincided, indicating closely related movements of these joints. The same principal characteristic can be observed while performing full (deep-knee) squats or countermovement jumps. Robertson et al. (22) calculated the average length of the muscle–tendon unit as a proportion of their standing length during full squats. The VL lengthened eccentrically by 18% of their standing length, whereas at the same time, the knee angle decreased from 160° down to 65°. However, the biarticular RF muscle remained close to its standing length with changes of less than 2%. Similar observations were made by Visser et al. (29) during the push-off phase of countermovement jumps, where only minor length changes of the muscle–tendon unit on the biarticular RF were observed. Although the range of motion during alpine skiing is less than half compared with a full squat, we assumed that the principal characteristic should be the same. Figure 7 contains the assumed changes in the muscle–tendon unit length based on our kinematic data and the calculation for a full squat (22). Similar predictions of length changes are made by the muscle–tendon unit calculations using SIMM Pipeline (Musculographics, Inc., Motion Analysis Corp, Santa Rosa, CA) and a model similar to the model by Delp et al. (5), with unpublished knee and hip angle skiing data as inputs. The SIMM model predicted that RF was at a nearly constant length throughout the double turn, whereas the VL is lengthened during the first part in the inside leg (time windows 1–4) followed by a

FIGURE 6—Trace of individual EMG intensity during a double turn (time windows 1–5 = inside leg, time windows 6–10 = outside leg) for two different subjects (X and Y) in the steep and flat inclination (triangles = steep, circles = flat). A, VL of subject X. B, RF of subject X. C, VL of subject Y. D, RF of subject Y. Note that this figure reflects means ± SD.
shortening from time window 4 to time window 6 and constant length throughout the outside leg phase. The predicted amount of length change was in the inside leg = 8.8%.

Doud and Walsh (6) reported almost a 1:1 ratio of strain to change in frequency (20% increase in length/18% fall in EMG frequency). Our data showed differences in frequencies in the inside leg compared with the outside leg of 11% (increase) for VL and 16% (decrease) for RF. Changes in the muscle–tendon unit length from the squat analogy (4% for VL and <1% for RF) and the prediction by the SIMM model are far too small to cause the observed change in frequency (especially for RF). To estimate muscle fiber behavior solely from the observation of joint performance is difficult because the fascicle does not behave exactly like the muscle–tendon unit (13). Looking at the curve of the muscle–tendon unit and muscle fascicle length in other activities that are similar kinematically to downhill skiing (stair ascent and descent [3] and drop jumps [13]), one can identify principal similarity of the courses for VL (shorten during knee extension, lengthen during knee flexion). Chleboun et al. (3) identified differences within the particular phases in length changes of the muscle–tendon unit and length changes of the fascicle in a range from −5.7% up to 6.5%. Adding those differences as worst-case scenarios to the assumed length changes of our study, we still do not have enough length change in the muscle to explain the change in MF of the EMG (6). Furthermore, it has been reported that as strain increases, MF should decrease (6). The results for VL (time windows 1–4; Fig. 5C) depict that the bigger strains result in higher frequencies, and this is opposite to what the length effect should be.

As described above, the higher mean frequencies observed for RF in the inside leg compared with the outside leg in the present study are not explainable by changes in muscle length alone. The pattern of motor unit recruitment is an important factor in shaping the myoelectric intensity spectrum. Action potentials from faster fibers travel at higher conduction veloci-

**Influence of Slope Inclination**

**EMG intensity content.** Increasing loads on the skeletal muscle system result in increased muscle activity, as assessed by EMG intensities (e.g., Kyrolainen et al. [16] and Wakeling et al. [36]). Clarys et al. (4) suggested that the inclination of the slope is a discriminating factor for muscular activity in alpine ski racing. Their results were presented as grouped results because the study of each muscle separately (six lower limb muscles) did not allow for the detection of a possible influence of the geography. This is mainly caused by two methodological procedures. First, the analyzed slope was
defined as relatively easy, with inclinations ranging from 10° to 18°. Second, they did not distinguish between the inside leg and the outside leg but calculated an overall integrated EMG for each movement cycle. Our data depict a more diverse picture according to the EMG intensities. Both muscles responded with higher EMG intensities to increased inclination. For the outside leg, substantial differences between the flat and the steep segments were observed for RF (+150%) and VL (+119%). For the inside leg, only RF (+93%) showed a substantial increase, whereas the VL (38%) increase was distinctly smaller. This is again an indication for the functional importance of RF on both turn sides, compared with the importance of VL in the outside leg, and goes inline with the previously discussed functional demand on the studied muscles.

Again, considerable interindividual variations were observed. Subject Y, for example, demonstrates three specific responses on increasing slope inclinations (Figs. 6C and D). First, the difference in EMG intensities between steep and flat is, with the exception of time window 7, in both muscles not that pronounced compared with the overall group. Second, we observed for both muscles in the inside leg two activation peaks (time windows 2 and 4) during the steep inclination compared with one peak (time window 4) during the flat section. The third inclination-specific response is earlier peak activation in the outside leg during the steep inclination compared with the flat one (again on VL and RF).

**EMG MF content.** From a physiological point of view, Scheiber et al. (23) demonstrated that when skiers are skiing the technique termed “carving in long radii” (37) on different steep slopes, a remarkable increase in physiological demand occurs. On the basis of the skiing level and the age of the subjects, we can assume that the skiing effort in the present study and in Scheiber et al. (23) was quite similar. Scheiber et al. (23) reported lactate levels after skiing on both slopes with the “carving in long radii” technique of 1.8 mmol·L⁻¹ for the flat and 3.0 mmol·L⁻¹ for the steep slope. Lactate concentration is positively correlated to individual muscle fiber composition expressed as a percent of fast-twitch fibers during alpine skiing (26). Therefore, it could be assumed that skiing on a steep inclination results in increased MF. The results of our study do not support this assumption because we found no direct relation to the inclination of the slope (Fig. 4). Wakeling et al. (36) reported a shift to higher frequencies because of increased muscle fascicle strain rates during cycling. The muscle fascicle strain rates were not measured directly during our experiment, but we assume that our kinematical data allow the conclusion that the strain rates were slow and rather constant throughout the different inclinations. This serves as a possible explanation for the nonincreased mean frequencies in the steep inclination.

However, different mean frequencies in the three pitches were observed, which seem to be caused by the progression within the measurement runs (first segment highest MF, third segment lowest MF). Because of our experimental protocol, a fatigue-related lactate increase occurred along the three segments. A study by Seifert et al. (24) on the same slope with similar skiing effort and subjects reported average lactate levels of 2.7 mmol·L⁻¹. The increase of metabolites, such as lactate, decreases the conduction velocity of the muscle unit action potential, and therefore, the EMG frequency spectrum shifts to lower frequencies (35). The increased lactate level during the runs seems to progressively decrease the MF, but on a rather small amount. The influence of the slope on MF per se is not apparent because muscle fascicle strain rates are rather constant throughout the inclinations. If muscle fascicle strain rates (36) are an important factor for altered muscle recruitment, then this could be an aim for further investigations, particularly with different skiing modes (curving long radii vs carving short radii), which may provoke different muscle fascicle strain rates.

**Wavelet Application in Alpine Skiing**

In this study, the myoelectric activities were resolved by wavelet analysis into their intensities and frequency in time space. This level of detail has been made possible by using wavelet analysis on the myoelectric signals, and this would not have been resolvable by root mean square (RMS) or Fourier transformation techniques alone (35). The advantage of wavelet analysis is that time resolution in both intensity and frequency is virtually unaffected. The MF used in this study is comparable to the mean power frequency from a Fourier transformed signal used to measure EMG contractions in several studies (e.g., MacIsaac et al. [17]). A Fourier transformation requires stationary signal behavior during a substantial time span (≥200 ms) (31) and causes a collapse in the temporal aspect of the signal. With the wavelet transformation used in the current study, the investigator has the possibility to define the reduction of data in time space. To describe our results, we reduced the information in time space in two different ways: first, into inside leg and outside leg; and second into 10 equal time windows (time windows 1–10). Those two methods seem to be an ideal compromise between holding time information and giving the possibility to summarize the information for statistical calculations (cf., Berg et al. [2]). For future research, we suggest combining this method with a more sophisticated statistical quantification (e.g., principal component analysis [32]) to answer scientific questions in alpine skiing such as the influence of “prolonged submaximal skiing” or “specific conditioning” on muscle recruitment.

**CONCLUSIONS**

One aim of the study was to study the functional aspects of different knee extensors muscles while recreational alpine skiing with the equipment used today. The hypothesis, that the muscle recruitment of VL is substantial in the inside, can only partially (for the flat inclination) be supported through our
study. However, the functional demand for RF in the inside leg is very high when skiing recreationally. The ability of a situation-dependent loading (RF as knee extensor) and unloading (RF as hip flexor) in the inside leg seems to be a crucial point with respect to specific fatigue during a skiing day. On the basis of the considerations of the changes in muscle length, the predominance of eccentric muscle activity as a unique feature of alpine skiing (e.g., Berg et al. [2]) has to be at least reconsidered for recreational skiing.

The second aim of the current study was to investigate the influence of the slope inclination during recreational alpine skiing. An increase in inclination resulted in increased EMG intensities, which goes in line with previous results of Clarys et al. (4) for expert-level skiing. Because of the separation in inside leg and outside leg and the progression through a double turn, we observed that RF responded on both turn sides, whereas VL responded only in the outside leg. These results demonstrate again the functional importance of RF.

For the third aim of the study (application of the wavelet analysis on alpine skiing EMG signals), we conclude that the method used is a powerful tool for an in-depth description of muscular activity during alpine skiing. Next to investigations on groups, this method is also a useful tool in quantifying individual skiing strategies/techniques (e.g., in alpine skiing racing).

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THE INFLUENCE OF SUSTAINED SUB-MAXIMAL SKIING ON THE FREQUENCY AND INTENSITY CONTENT OF THE EMG SIGNAL
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Quantifying fatigue processes in alpine skiing could be helpful in improving comfort, enjoyment and safety issues. It has been shown that muscle activity changes during fatiguing exercises to exhaustion. Due to the fact that these changes can be observed in amplitudes / intensities and frequency contents of a signal, a method covering both aspects is essential. As with other dynamic exercises, the intensity analysis in time-frequency space of EMG signals by wavelets is a powerful analytical tool in alpine skiing (Kroell 2007). The purpose of this study was to investigate the influence of a sub-maximal skiing session on EMG frequency and intensity content of rectus femoris RF by the use of wavelets. Seven female subjects performed 21 runs on a slope with 300 m elevation. Knee angle and EMG of RF (right leg) was measured during runs 2, 23 and 24 (1st PRE; 23+24=POST; 21+24=POST1; 24=POST2). Knee angle and raw EMG were used to determine the start and end of each double turn (1st turn right leg = inside leg [IL]; 2nd turn right leg = outside leg [OL]). The EMG signal of each run was resolved with a wavelet transformation into intensities for each point in time (10 centre frequencies between 19.3 and 30.6 Hz; von Tschamer 2000). 14 double turns from the last segment of each run and each subject were used to calculate a representative turn. For descriptive analyses, intensity spectra were calculated for ten evenly spaced windows of each double turn. 3D intensity plots were then created. For statistical analyses, intensity spectra were calculated for IL and OL. A 1-way ANOVA with RM was used to analyze mean intensity and frequency for IL and OL.

A downward shift in mean frequency was observed for IL (82.1Hz; 79.4Hz; p eta2=.22; p<.019) and OL (71.3Hz; 68.3Hz; p eta2=.50; p<.004) between PRE and POST. Higher intensity values for IL (+15%); p eta2=.15; p<.439) and OL (+22%); p eta2=.16; p<.314) were observed for POST compared to PRE. However the treatment effect is clearly lower compared to the frequencies. The change between PRE and POST is larger than the change between POST1 and POST2 for the frequencies in IL (eta2=.41; p<.009) and OL (eta2=.53; p<.004). The changes in intensity were not different for PRE vs. POST and POST1 vs. POST2 for IL (eta2=.00; p<.930) and OL (eta2=.01; p<.879).

Previously, alpine skiing researchers extracted only intensity and timing data from EMG. Our data demonstrate that the quantification of sub-maximal fatigue by intensity alone does not identify signal changes. This may be due to the high variability caused by the complex movements in alpine skiing from turn to turn and from run to run compared to e.g. isometric tasks. However frequency changes can be explained by the sub-maximal skiing treatment (run 3 to run 23). It is recommended that the focus be on frequency more than intensity in the description on muscular fatigue during alpine skiing.
Introduction

In many regions in the world, alpine downhill skiing is one of the most popular and most frequently practiced form of winter sport. In alpine regions, this fact is of high significance above all from economic, social, and health aspects. Within the last 20 years, the ski industry created a very successful innovation with the development of the carving ski system. In ski racing as well as in recreational skiing, skis have become much shorter, their side cut has increased to a great extent and binding plates (risers) have been fixed between the ski and the binding. In addition the stiffness of the ski has also changed. This evolution has, of course, also changed the movement patterns of performing ski turns; yet it might also have changed the risk of sustaining injuries. This chapter will give an overview on the dynamics of downhill skiing techniques. This will be followed by a comparison of biomechanical aspects of traditional and carving turning techniques in recreational skiing. Finally, some new insights into muscle fatigue during recreational skiing will be given.

The Dynamics of Downhill Skiing

In the following paragraph, an overview of the external forces working on the skier’s body is given. We differentiate it into the three important skiing techniques, gliding straight down the fall line, gliding straight across the slope, and performing a turn (Müller et al., 2008).

Straight Gliding Down the Fall Line

At the system skier-ski the gravitational force $F_G$ acts at the CoG. This force can be divided into two force components, $F_S$, the force parallel to the slope plane that causes the acceleration of the skier and $F_N$, the normal or perpendicular force to the slope (Figure 5.1).

The size of each of these forces depends on the angle $\alpha$ of the slope:

$$F_S = F_G \times \sin(\alpha)$$

$$F_N = F_G \times \cos(\alpha)$$

The force $F_{\text{reac}}$ represents the reaction of the snow to the ski. It is the sum of the distributed forces due to the snow pressure on the bottom of the ski. $F_{\text{reac}}$ works in the opposite direction of $F_N$. (Müller, 1991; Howe, 2001; Lind & Sanders, 2004). The forces $F_N$ and $F_{\text{reac}}$ cause a torque ($M$), when the lines of action of those forces do not coincide.

The skier is decelerated by the snow friction force $F_f$ and the air frictional force $F_D$, which are directed opposite to the skier’s velocity. In a simplified model, the snow friction force that acts along the contact area between ski and snow depends on...
real-performed turns in skiing. It could be shown that CTs without any skidding hardly seems to be possible. But it could also been shown that the amount of skidding during turns differs a lot within the various turning techniques.

**Muscle Functions and Muscle Fatigue in Recreational Skiing**

Surface EMG is often used to evaluate muscle activity during movement. A review of EMG literature during alpine skiing indicates that amplitude and timing pattern of muscle activity have been analyzed along with the relative activity of different muscles (Berg et al., 1995, knee extensors). Due to the involvement of different muscle fiber types (slow- and fast-twitch fibers) and their different motor unit action potentials, the frequency of an EMG signal contains additional information about muscle fiber activation. When a muscle is active, the fast fibers can generate higher frequencies within the signal than slow fibers (Wakeling, 2009). Furthermore, muscle fatigue results in changes to both the amplitude/intensity and frequency contents of an EMG signal. Thus, to describe muscle activity during alpine skiing adequately, a method covering both aspects is essential.

The analysis of the frequency content by calculating the median power frequency (Kroell et al., 2005) resulted in the loss of timing information, which is essential in alpine skiing research. Developments in wavelet analyses for EMG permit the signal intensities to be simultaneously resolved in time and frequency, with time resolutions in the order of 20 ms (von Tscharner, 2000). The resulting intensities are a close approximation of the signal power contained within a given frequency band at each time point. This presents the possibility to visualize the EMG intensity pattern of a movement in time–frequency space during each cycle of a movement as it has been previously demonstrated for running and cycling (von Tscharner, 2002; Wakeling, 2004). Due to the primarily cyclical movement patterns in alpine skiing, which is comparable to running and cycling, there appears to be potential for a more in-depth analysis of muscle activity during alpine skiing by the use of wavelets.

In a study investigating a group of 10 recreational skiers (Kroell et al., 2008, 2009), subjects had to ski 24 runs through a standardized corridor on a slope with 300 m elevation with a medium inclination (21°). On average, 11 double turns (one right plus one left turn) per run were performed. Knee angle and EMG of RF and VL of the right leg were measured during runs 1, 2, 23, and 24. Knee angle and raw EMG were used to determine the start and the end of each double turn (first turn right leg = inside leg [IL]; second turn right leg = outside leg [OL]). The EMG signal from each run was resolved with a wavelet transformation into intensities for each point in time (10 center frequencies between 19.3 and 395.4 Hz; von Tscharner, 2000). Thereafter, the mean intensity spectrum was calculated for 10 evenly spaced windows (time windows 1–10) of each double turn. For each subject, all double turns of run 1 and run 2 were used to calculate a representative turn for the START of the skiing session. The same was done with run 23 and run 24 for the END of the skiing session. To get a representative result for the group, the same was done over all subjects for START and END. With those values, 3D intensity grid-plots for the overall group were created (Figure 5.14). Those plots represent wavelet 1 to wavelet 9 on the vertical axis represented by center frequencies (19–331 Hz) and the time information by time windows (1–10) on the horizontal axis. The intensity is represented by the shading, where bright means high intensity and dark denotes low intensity.

Differences in timing, intensity, and frequency content of RF and VL can be observed in the 3D plots (Figure 5.14). VL is active throughout the double turn with maximum intensities during TW7–8 where the measured right leg is the OL. In contrast, RF shows a biphasic activity with two clear maxima on IL (TW3) and OL (TW8) and low activity during edge changing from IL to OL (TW5–6). Due to the fact that current skiing technique has changed to a more bilateral style (Mueller & Schwameder, 2003), one could assume that there would be higher activity during IL. Although the skiers performed a modern recreational carving technique, the predominant unilateral use (OL) of the one-joint knee extensor VL seems to be given. The contrasting
Biphasic patterns of RF suggest that this two-joint muscle works not only as knee extensor during OL, but also as a hip flexor and/or knee extensor during IL. We assume that there is currently a situation-dependent loading (RF as knee extensor) and unloading (RF as hip flexor) necessary which is reflected in the EMG activity.

According to the frequency content, one can observe on VL the greater involvement of higher frequencies during OL compared to IL. In contrast, the results of RF clearly indicate a more pronounced involvement of higher frequencies on IL compared to OL. Doud and Walsh (1995) reported almost a 1:1 ratio of muscle fiber length changes to change in frequency (20% increase in length/18% decrease in EMG frequency). It is very unlikely that the differences in frequencies between IL and OL are caused by changes of the fiber length. Especially, the muscle fiber length of the biarticular RF remains in a rather constant length during alpine skiing, due to the closely related movement of the hip and knee angle (Berg et al., 1995, minimum and maximum angle coincided). Hence, the fiber strains are too small to explain the changes in frequency and therefore the most likely explanation for the differences in frequency content are from changes in recruitment. Those changes in recruitment of RF may provide additional information on the functional characteristics of the muscle during skiing. It is possible that RF recruits more fast fibers during IL (higher frequencies) compared to more slow fibers during OL. With the already mentioned functional skiing technique aspects, this would mean that RF recruitment, and specifically the fast components, is an important steering factor during IL. The ability to recruit fast RF fibers over a substantial time (hundreds of IL turns during a day) seems to be a crucial aspect in alpine skiing. The appropriate motor unit recruitment maybe necessary to obtain a good bilaterally loaded skiing technique through knee extension of the IL, or to reduce the loading of the IL through hip flexion. A potential consequence of high loading of the IL is a fall due to over edging.

Figure 5.15 represents the changes in muscle activity of the biarticular RF from the beginning to the end of a 3h skiing session. One can observe very specific changes in terms of timing, intensity, and frequency caused by the 3h skiing intervention. There is a slight increase in muscle activity (Figure 5.15 [+] ) at the last part of IL (TW 4 and 5) and a clear increase at the last part of OL (TW 9 and 10).
Figure 5.15: Changes of muscle activity during a 3h skiing session. (a) Intensity plot over time and frequency of rectus femoris (RF) for the overall group at START and END of the skiing session. (b) Plots of differences representing [+] as increasing intensities and [−] as decreasing intensities. IL, inside leg; OL, outside leg; WL, wavelet.
On the other hand, a decrease (Figure 5.15 [—]) during the earlier IL (TW 2 and 3) and OL (TW 6, 7, and 8) phases can be observed. According to the frequency content of the signal, one can observe that higher frequency components are decreased during IL (TW 2 and 3). Figure 5.15 [—]) and lower components are increased during OL (TW 9 and 10). Figure 5.15 [—]). Due to very similar knee angles at the START and END of the skiing session, the changes in the frequency content are again more recruitment related than muscle length. There seems to occur fatigue-related recruitment changes which are detrimental regarding the above-described importance of RF (specifically the fast components) as steering factor on IL. Due to the prolonged skiing session, the effects for skiers to initialize the next turn. The result is a more pronounced activity at the last part of the turn instead of a homogenous activity throughout the turn at the beginning of the skiing session. From a functional perspective, this could mean a potential risk of falls due to higher dynamic components at the end of the turn which increases the efforts for skiers to initialize the next turn.

Using the wavelet analysis gives the potential to extract conventional intensity and timing information as well as additional information about the frequency content of the signal. Due to this possibility, the principal differences of the two-joint RF and the one-joint VL were described with greater depth and detail than by the common methods used by Berg in 1995. Consequently, the results should be considered in the physical preparation of alpine skiers (high demand on the biarticular RF) and teaching/guiding concepts (ski instructors) of recreational skiers to reach improved IL steering by adequate loading in general, as well with increasing fatigue during a skiing day.

References


Changes in quadriceps muscle activity during sustained recreational alpine skiing

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ABSTRACT
During a day of skiing thousands of repeated contractions take place. Previous research on prolonged recreational alpine skiing show that physiological changes occur and hence some level of fatigue is inevitable. In the present paper the effect of prolonged skiing on the recruitment and coordination of the muscle activity was investigated. Six subjects performed 24 standardized runs. Muscle activity during the first two (PREskiing) and the last two (POSTskiing) runs was measured from the vastus lateralis (VL) and rectus femoris (RF) using EMG and quantified using wavelet and principal component analysis. The frequency content of the EMG signal shifted in seven out of eight cases significantly towards lower frequencies with highest effects observed for RF on outside leg. A significant pronounced outside leg loading occurred during POSTskiing and the timing of muscle activity peaks occurred more towards turn completion. Specific EMG frequency changes were observed at certain time points throughout the time windows and not over the whole double turn. It is suggested that general muscular fatigue, where additional specific muscle fibers have to be recruited due to the reduced power output of other fibers did not occur. The EMG frequency change and intensity changes for RF and VL are caused by altered timing (coordination) within the turn towards a most likely more uncontrolled skiing technique. Hence, these data provide evidence to suggest recreational skiers alter their skiing technique before a potential change in muscle fiber recruitment occurs.

Key words: Muscle Coordination, Recruitment, Electromyography, Wavelet Analysis

INTRODUCTION
During sustained recreational alpine skiing our bodies experience changes during the day that alter the way in which we perform. From a physiological point of view we can consider that recreational alpine skiing reaches a state of fatigue where physiological changes occur yet the activity can still be sustained. Those physiological processes are described within the skiing sports science literature for both, alpine ski racing (Turnbull et al., 2009) and recreational alpine skiing (Scheiber et al., 2009, Seifert et al., 2009, Tesch et al., 1978) as well. For recreational skiing fatigue is associated with increased risk of injury and reduced pleasure of the activity (Hunter, 1999). An increase in the number of injuries after 2-3 hours of skiing has been previously attributed to fatigue in adult skiers, with the incidence of injury increasing as the day progresses (Meyers et al., 2007). A more in-depth understanding of ongoing changes in muscle activity during a prolonged skiing session would provide an extension of primarily physiological measures previously reported in the literature. Knowing how skiers change their overall skiing technique based on shifts in control or altered recruitment within a muscle would serve useful information not only to improve the comfort and enjoyment, but also the safety in recreational alpine skiing (Hintermeister et al., 1997).

One consistent finding of the previous work is that there is a high level of effort by the knee extensor muscles during skiing. Numerous authors have reported that muscle contraction forces can reach upwards of 100-150% of maximal voluntary contraction (MVC) in the outside leg when making a turn (Berg et al., 1995, Hintermeister et al., 1997). Recently specific functional demands on the different knee extensor muscles in recreational skiers have been investigated (Kröll et al., 2010). Contrary to previously shown co-loading of the inside leg while skiing carving turns (Mueller and Schwameder, 2003), the results for the vastus lateralis muscle (VL) did not support the co-loading function for recreational skiing (Kröll et al., 2010). This muscle seems to be relatively inactive for the inside leg. However, they showed the functional demand for rectus femoris muscle (RF) of the inside leg is very high when skiing recreationally (Kröll et al., 2010). Assuming this is accurate, the demand on RF is greater compared to VL. This is most likely due to its dual function of influencing knee extension and hip flexion, for either the inside or outside leg.

Prolonged submaximal or maximal muscle contractions affect the capacity of muscles to generate forces (Smilios et al., 2009) and alters muscle activity as measured by surface electromyography (EMG) (Wakeling et al., 2001). These alterations occur and are quantified in three different domains:

EMG intensity domain: The integrated EMG signal during a moderate load muscular endurance session (squat exercise; 4 sets of 20 repetitions; 50% of one repetition maximum) increases within each set and from set to set (e.g.: squat exercise; 4 sets of 20 repetitions; 50% of one repetition maximum; Smilios et al., 2009). This increase has been attributed to the recruitment of the additional muscle fibers required to overcome fatigue and maintain power output.

EMG frequency domain: A decrease in the frequency content of the EMG signal at maximum workloads can be observed during fatigue (e.g. So et al., 2009). These
changes have been related to different mechanisms. A decrease in conduction velocity occurs with an increase in metabolites such as lactate (Brody et al., 1991). Recruitment adaptation within the muscle to maintain the power output is another possible reason since motor units with higher mean frequency tend to fatigue to a greater extent than those with relatively lower mean frequency (Moritani et al., 1982). Wakeling and Pascual (2001) reported a significant reduction in EMG intensity at low frequencies and a significant increase at high frequencies for submaximal running which is different to the fatigue related changes seen for maximal fatiguing contractions (So et al., 2009). However, they suggest that the pattern of muscle recruitment may change during sustained submaximal exercise.

**EMG time domain (Coordination of the muscle, e.g. on/off):** Although pedaling is standardized to a large extent since a bicycle constrains lower extremity movements, alterations in the coordination strategies during exhaustive pedaling exercise can be observed. (Dorel et al., 2009). Apriantono et al. (2006) showed for the instep kicking task in soccer that induced leg muscle fatigue disturbs kicking performance, leads to a less coordinated kicking motion, thereby making players more susceptible to injury. For a task such as alpine skiing, where the coordinative demand is very high, it can be assumed that alterations in coordination strategies may occur to a certain degree thus yielding an altered mechanical output that might also be less functional.

Hence, surface EMG requires analysis methods which permit the signal intensities to be simultaneously resolved in time and frequency domains to quantify alterations in muscle activity caused by fatigue. Among different time-frequency analysis methods, wavelet transform has been reported to be appropriate for analyzing the EMG signal during dynamic contractions (Karlsson et al., 2000, von Tscharner, 2000). The wavelet decomposition technique has been previously used for several dynamic tasks in non-fatigued (e.g. Wakeling et al., 2006), sub-maximal fatigued (von Tscharner, 2002, Wakeling et al., 2001) and maximal fatigued exercises (So et al., 2009). This method was previously applied to recreational alpine skiing to gain functional insights in the knee extensor muscles. (Kröll et al., 2010).

Consequently, the aim of the present study was to investigate how knee extensor muscles respond to submaximal fatigue during recreational alpine skiing with respect to the recruitment and coordination of the muscle activity. As representative knee extensor muscles the one joint VL and two joint RF were investigated. We hypothesized that there would be changes in the intensity and frequency domain as well as in the general coordination pattern of muscle activity within the main knee extensor muscles during a recreational skiing session. Due to the higher functional demand on RF compared to VL (Kröll et al., 2010) the magnitude of these changes were expected to be larger on the biarticular RF.

**MATERIALS AND METHODS**

The current study is a part of a larger project in recreational alpine skiing. In Part One, the relationship and prediction of common physiological fatigue indices during downhill skiing (Seifert et al., 2009) were investigated. In Part Two, the functional aspects and muscle recruitment of selected knee extensor muscles were addressed (Kröll et al., 2010). This paper addresses the effect of prolonged skiing on the recruitment and coordination of muscle activity. As the data collection occurred simultaneously with Parts One and Two, some methodological details will be referred to from these previous publications.

**Subjects**

Ten healthy female subjects (22.7 yr ± 4.0 s.d.) provided informed consent to participate in this study. The local Ethics Committee of Salzburg approved the research protocol and all participants were fully acquainted with the nature of the study before they gave their informed written consent. To get a homogenous sample, subjects were selected according to their skiing ability and amount of skiing days per year. All subjects were of the intermediate level based on the Austrian Ski Teaching Concept (Woerndl, 2007). Intermediate level skiers are able to perform short and long radii turns on prepared terrains. In flat terrain, intermediate skiers are able to execute carved turns, but perform mostly skidded turns on steep terrain.

**Experimental Design**

All subjects followed a standardized 15 minute warm-up on a cycle ergometer and two warm-up runs on the ski slope. Skiers were then instructed to perform two measurement runs to determine the PREskiing condition. Then the skiers had to perform 20 runs where no biomechanical data collection took place. Finally skiers performed two measurement runs to determine the POSTskiing condition. To standardize the length of turns and distance skied across the fall-line, subjects skied for all 24 runs through a standardized corridor. The skiing session lasted about three hours in which the total skiing time was about 40 minutes. Within each run, there were three pitch changes; for this study only the first one (top of run (TOP), 21°, on average 22 turns) and the last one (end of run (END), 13°, on average 28 turns) were considered. For more detailed information concerning the slope and the skis used see elsewhere (Kröll et al., 2010, Seifert et al., 2009).

**Physiological Measurements**

Overall run time and heart rate (HR) at the end of each run was recorded (Polar, Finland). To reach a standardized load during the skiing session, verbal feedback on finishing time and HR were provided to each skier at the end of each run as absolute values. For further analysis percent of maximal HR (%HRmax) was
calculated using 220 – age. Earlobe blood samples in the amount of 20 microliters were collected following the second (PREskiing) and immediately after the 24th (POSTskiing) run. The blood samples were analyzed for lactate (LA) (Biosen 5140, EKF-Diagnostic GmbH, Magdeburg, Germany). LA was considered as control parameter for interpretation of the shifts in EMG spectrum since the level of accumulated LA indicates a close relation to the shift in the EMG spectrum towards lower frequencies during fatigue (Horita and Ishiko, 1987, Tesch et al., 1983).

EMG and Kinematics Measurement

Data acquisition took place unilaterally on the right leg. Myoelectric activity was measured from the vastus lateralis (VL) and rectus femoris (RF) muscles using round bipolar surface electrodes (Ag/AgCl; 10mm diameter, 22mm spacing). The sensor placement procedure was based on the SENIAM recommendations (Hermens et al., 2000). The EMGs were amplified at source (bandwidth 10-500Hz, 3dB; Biovision, Wehrheim Germany) and recorded at 2000Hz (Daqcard-700, National Instruments, Austin, TX, USA; iPAQ H3800, Compaq, Houston, TX, USA). Simultaneously, a goniometer mounted on the knee joint measured the occurring knee angle (note that 180° was defined as full extension). The knee angle and myoelectric activity were recorded for the entire four measurement runs (two PREskiing / two POSTskiing).

Wavelet and Principal Component analysis of EMG during alpine skiing

Compared to a previous study (Kröll et al., 2010), methods used in the current study added a principal component analysis of the EMG spectra to quantify spectral shifts (Wakeling and Rozitis, 2004). The main information is derived by the first two principal components (PC I and PC II). Additional variations in the original spectra’s (e.g. movement artifacts and motor unit synchronisation) are partitioned into lower components and hence, do not obscure the main information of interest (Wakeling, 2009). Therefore it is suggested that the principal component technique is more sensitive to major changes in the EMG spectra that occur during movements and locomotion.

Wavelet transformation

The entire raw EMG signal (Figure 1A) was resolved with an EMG-specific wavelet transformation. The intensity was calculated using a filter-bank of wavelets following von Tscharner (2000). Each wavelet has a frequency band and the time-varying intensity is calculated for this band. For each moment in time the EMG is thus represented by its intensity at a range of frequency bands (11-432Hz), and this is termed the intensity spectrum.

Turn separation and time frame within a double turn

A combination of knee angle and raw EMG was used to determine the start and end of each double turn. A double turn was defined as where the right leg is the inside leg during the first turn and then is the outside leg during the second turn (Figure 1A). For 10 equal time windows along the double turn and each single wavelet the mean value of intensity was built to generate a 3-dimensional grid (X= Time; Y Frequency; Z=Intensity as shown in Figure 1B for one double turn). The mean intensity spectra was calculated for the overall double turn and was used for EMG intensity normalization (for details see Kröll et al., 2010). The overall inside leg and the overall outside leg are shown in Figure 1C. Furthermore the mean knee angle of the overall inside leg and the overall outside leg within the double turn was also calculated.

Elimination of artifacts and subjects:

The same method for eliminating artifacts was used as previously described (Kröll et al., 2010). Compared to the paper with the functional analysis (n=7), due to additional artifacts in the POSTskiing session one additional subject had to be excluded. This reduced the total number of subjects used in this analysis to six.

Principal Component Analysis

For the analysis n=2223 normalized intensity spectra from the different subjects (n=6), turn side (inside leg=1062, outside leg=1161), conditions (PREskiing n=1080, POSTskiing n=1143), run part (TOP n=984, END n=1239), and muscle (VL n=1111, RF n=1112) were considered. Each of the intensity spectra contained 10 intensities corresponding to the wavelets 1-10 and a frequency band from 11-432 Hz (Figure 1C). All of the 2223 spectra were compiled into a data matrix. The covariance matrix was calculated from the data matrix, and used to calculate the principal components (PC) (Wakeling and Rozitis, 2004). The principal components were calculated with no prior subtraction of mean data and describe the components of the entire signal (Wakeling and Rozitis, 2004). Each EMG intensity spectrum can then be reconstructed from the vector product of the PC weightings and the PC loading scores (Figure 2). The PCs are defined by the PC weightings that are the eigenvectors for the covariance matrix, and the PC loading scores that quantify the contribution of each eigenvector to the measured signal. The majority of the signal for any given myoelectric spectrum is defined by the first two PCs (PC I and PC II). The weighting for PC I has a shape similar to that for a myoelectric intensity.
Figure 1: (A) EMG trace and knee angle from the vastus lateralis (VL) during one double turn. (B) Myoelectric intensity of the turn is shown as a function of time and frequency, with high intensities denoted by dark shading. Ten time windows divide the overall double turn in different time frames. They are indicated by the vertical white lines. (C) Myoelectric intensity spectra for inside leg, outside leg and the overall double turn shown in (B).
Figure 2: Principal component representation of EMG frequency spectra. Weighting for (A) the first principal component (PC I) and (B) the second principal component (PC II). (C) EMG-intensity spectra that can be reconstructed from vector products of the PC weightings shown in (A&B) with 0.5 PC I + 0.3 PC II shown in black and 0.5 PC I – 0.28 PC II shown in grey. The mean frequencies (MF) for the reconstructed spectra are shown. (D) Vector representation of the spectra in (C) following the same colors and symbols as in (C). The angle $\theta$ is a measure of the relative PC I and PC II loading scores and of the myoelectric frequency.

The hypothesis that the myoelectric frequency differed between PRE- and POST-skiing due to the submaximal skiing session was tested with an analysis of covariance (ANCOVA). The response variable was $\theta$. Subject code, time of measure, and slope part were used as factors in the test. The myoelectric intensity was used as a covariate in order to establish whether the shifts in myoelectric frequency in this study were independent of variations in myoelectric intensity (Wakeling, 2009). The ANCOVA was repeated for both muscles (VL, RF) and both turn sides (inside leg, outside leg).

The hypothesis that myoelectric intensity between PRE- and POST-skiing differed was tested with a three factor ANOVA (subject code, time of measure, slope part). The response variable was the PC I loading score. The ANOVA was also repeated for both muscles and both turn sides. All data are presented as mean ±standard error of the mean (s.e.m) and statistical tests were deemed significant at $\alpha$=0.05 (tendency $\alpha$=0.1). Effect size measures (and interpretation) included partial eta squared ($\eta^2$) for all ANOVA.

Statistics

Repeated measures (RM) analysis of variance (ANOVA) was used to test differences in PRE- to POST-skiing load (for overall run time, %HRmax and LA). Differences in PRE- to POST-skiing knee angle were tested with a $2_{(\text{Time})} \times 2_{(\text{Slope Part})}$ RM-ANOVA which was performed for inside leg and outside leg separately.

spectrum (Wakeling and Rozitis, 2004). Furthermore it is expected that the myoelectric intensity is highly correlated with the PC I loading score ($r^2>0.95$) (Wakeling et al., 2006). The relative loading scores of PC I and PC II give a measure of the frequency of the myoelectric signal (Wakeling, 2004). The angle $\theta$ was defined by the direction of the PC I-PC II loading score vector for each EMG intensity spectrum. Angle $\theta$ was then used as a measure of the mean myoelectric frequency for each EMG-intensity spectrum (for each turn), respectively (angle $\theta$ = arctan (PC I score/PC II score) (Wakeling, 2004).
Alterations in the specific coordination patterns of RF and VL (within each and between these two muscles) are described using 3-dimensional grids. Furthermore the course of the total intensity (calculated as the sum of the intensities within each spectrum) along the 10 time windows within each double turn are presented for PRE- and POSTskiing, each muscle and slope part. To get representative results for one subject the mean over all turns in a certain situation was calculated. To get a representative result for the group the same was done over all subjects.

RESULTS

Physiological Parameter and Knee Angle

Figure 3A depicts the overall run time for all skiers. The within subject range in finishing time was consistent and therefore no significant effects between PREskiing (100±0.9 s), prolonged skiing session (103.2 ± 1.4 s) and POSTskiing (99.8 ± 1.2 s) were observed. Although the HR response showed pronounced variation between subjects, within subject range during the 24 runs was consistent (Figure 3B). PREskiing %HRmax (81.9 ± 3.9%), prolonged skiing session %HRmax (78.1 ± 4.2%) and POSTskiing %HRmax (82.3±3.6%) were not significantly different. Average blood LA concentration was 2.72±0.53 mmol·L⁻¹ after the second run. Blood LA concentration decreased significantly by the 24th run to 2.13±0.46 mmol·L⁻¹ (p<.035, $\eta^2=.814$). Individual LA values ranged from 1.24-4.45 mmol·L⁻¹ after the 2nd run and from 0.89-3.63 mmol·L⁻¹ after the 24th run (Figure 3C).

The average knee angle on the inside leg was relatively consistent between the two pitches and at the PREskiing
and POSTskiing condition (PREskiing_TOP = 99±6°, POSTskiing_TOP = 97±5°, PREskiing_END = 96±6°, POSTskiing_END = 92±6°). Hence, the average knee angle of the inside leg was not significantly different between the PREskiing (97±6°) and POSTskiing (95±6°) condition. The average knee angle on the outside leg was also relatively consistent in the four situations (PREskiing_TOP = 115±5°, POSTskiing_TOP = 114±5°, PREskiing_END = 114±4°, POSTskiing_END = 110±4°) with no significant influence observed due to the prolonged skiing session (PREskiing 115±4°; POSTskiing 112±4°).

Overall inside leg and outside leg EMG results

The PC’s were calculated from the matrix of spectra for the inside leg and outside leg EMG-intensity spectra. The first two principal components of the myoelectric intensity spectra described 97.3% of the signal. The PC I weighting (Figure 2A) took a similar form to an EMG power spectrum (Figure 1C). The myoelectric intensity for each turn correlated with the PC I loading score with a correlation coefficient of $r=0.99$. The PC II weighting shows negative and positive regions with a crossover at about 60 Hz (Figure 2B). Intensity spectra could be reconstructed from the vector product of the PC weightings and the PC loading scores. Reconstructed spectra with positive intensities across all frequencies (a physiological constraint) occur for a range of $\theta$ and result in two extreme spectra with mean frequencies of 46.8 Hz and 105.7 Hz (Figure 2C).

Plotting the mean scores for PC I and PC II for all analyzed situations (Figure 4), one can identify several distinct populations of activity. A distinct difference between inside leg (dashed circle) and outside leg (solid circle) is given for both muscles. Clearly higher intensities (= PC I loading) were observed for inside leg compared to outside leg for VL, while RF shows similar intensities on both turn sides. According to the angle $\theta$ (measure of myoelectric frequency) it was found that the value was smaller (=higher myoelectric frequency) compared to the outside leg for RF at all inside leg situations. The opposite was observed for VL, depicted by higher $\theta$ (=lower myoelectric frequency) for all inside leg situations.

Timing aspect within a double turn (Figure 5)

Figure 5 contains descriptive information about changes caused by the prolonged skiing session with respect to timing aspects for the overall group. It can be noted that peaks in overall EMG activity occurred later in seven out of eight situations (turns) in the POSTskiing compared to the PREskiing situation (exception: VL inside leg TOP of run). Alterations within the different frequency band are shown by the grid plots. Alterations in RF are different between TOP and END of the run. A decrease in the higher frequency bands in time windows |2|3|7|8| and an increase in the lower frequency bands in time window |4|5|9|10| can be observed on TOP. A decrease in the higher frequency bands in time windows |2|3|4| and an increase in lower frequency bands on the whole outside leg (|6|7|8|9|) can be seen during END.

Figure 4: Principal component loading scores for PC I and PC II during recreational alpine skiing for m. vastus lateralis (VL, left graph) and for m. rectus femoris (RF, right graph). Each point shows the mean ± s.e.m. loading scores pooled from the six subjects. Data points within the solid circle represent outside leg while points within the dashed circle represent inside leg (solid symbols = PREskiing; open symbols = POSTskiing; circles = TOP of the run; squares = END of the run). The direction of the vectors in the PC I-PC II scoring plane represents angle $\theta$ and is visualized by solid (outside leg) and dashed lines (inside leg).
Figure 5: Alterations in timing aspects from PREskiing to POSTskiing of m. rectus femoris (RF) and m. vastus lateralis (VL). Left column of diagrams represent results for TOP of the run while right column represent END of the run. From top to bottom: PREskiing grid plot for RF, POSTskiing grid plot for RF (high intensities = dark shading); shift from PRE to POST for RF (blue = decrease, white = unchanged, red = increase); course of total EMG intensity for RF, course of total EMG intensity for VL (PREskiing = solid, POSTskiing = dashed).
Table 1: Probabilities from the analysis of covariance (ANCOVA) for the angle Θ and the analysis of variance (ANOVA) for the PC I loading score. The direction of changes is depicted by the arrows (↓=decrease; ↑=increase)

<table>
<thead>
<tr>
<th>Angle Θ</th>
<th>RF</th>
<th>PC1 Loading</th>
</tr>
</thead>
<tbody>
<tr>
<td>VL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inside Leg</td>
<td>Outside Leg</td>
<td>RF</td>
</tr>
<tr>
<td>520</td>
<td>591</td>
<td>542</td>
</tr>
</tbody>
</table>

Subject

p value  .000  .000  .000  .000  .000  .000  .000  .000

effect size $\eta^2$  0.811  0.808  0.45  0.826  0.374  0.323  0.149  0.472

PRE to POST

p value  .000  .000  .001  .000  .000  .000  .037

increase / decrease  ↑  ↑  ↑  ↑  ↑  ↑  ↑
effect size $\eta^2$  0.041  0.055  0.023  0.118  0.008

Post Hoc: PRE to POST

TOP

p value  .000  .000  .035  .024

increase / decrease  ↑  ↑  ↓  ↓
effect size $\eta^2$  0.076  0.064  0.196  0.019  0.022

END

p value  .066  .000  .001  .000  .001  .000  .000  .000

increase / decrease  ↑  ↑  ↑  ↑  ↑  ↑  ↑
effect size $\eta^2$  0.013  0.054  0.039  0.099  0.031  0.104

DISCUSSION

If classic fatigue exercises are defined as activities that cannot be sustained, then a normal recreational alpine skiing session (and the majority of daily tasks) does not reach a fatigued state. This study did not use a classic fatigue exercise protocol where the activity could no longer be sustained. Rather, this study employed a typical 3 hour skiing session at an intensity where physiological changes toward a fatigued state have been reported to occur (Seifert et al., 2009, Tesch et al., 1978) and which is indicative of typical recreational skiing.

The blood lactate level, which was recently reported to be a significant predictor for chronic stress (Seifert et al., 2009), was similar to a previous study on recreational skiers (Scheiber et al., 2009). With verbal feedback on overall run times and HR, skiers were able to maintain a constant load. A protocol identical to the present study reported base line values increased for salivary cortisol (16%) and creatine kinase levels (42%) (Seifert et al., 2009). The same study showed that muscle performance was influenced by the fact that isometric knee extension endurance decreased by 12%, but peak force was not different from PREskiing to POSTskiing. Hence, the notion that fatigue identifiable at sub maximal levels can occur within 24 runs of recreational skiing seems reasonable.

Distinct differences between inside leg and outside leg were observed in the same manner as seen previously in recreational alpine skiing (Kröll et al., 2010). Co-loading of the VL on inside leg was not observed while RF showed pronounced activity on both turn sides and the frequency content in RF of the inside leg points out a pronounced involvement of fast fibers. Furthermore, the current results demonstrate that the spectral properties and the overall intensities of muscle activity are affected by the prolonged three hour skiing session, and that the greatest effects can be observed in RF which supports our assumptions based on its functional demand (Kröll et al., 2010).

Changes in the myoelectric spectra caused by the prolonged skiing session

A shift towards lower frequencies was observed for POSTskiing for the mean frequency. Even though our results are consistent with general fatigue effects (decreased EMG frequency) there are several mechanisms which can shape myoelectric intensity and determine the myoelectric frequency (Wakeling et al., 2001). Possible mechanisms will be discussed, with particular focus on whether these can explain the changes in frequencies that were measured in this study.

Influence of muscle length

To discuss the changes in mean frequency of the EMG signal during a prolonged skiing session, it is necessary to estimate changes in muscle length since Doud and Walsh
(1995) reported decreased frequency is caused by increased muscle length (20% increase in length with an 18% decrease in EMG frequency). To estimate muscle fiber behavior solely from observation of joint performance is difficult since the fascicle does not behave exactly like the muscle-tendon unit (Ishikawa et al., 2003). Nevertheless, in a previous alpine skiing study (Kröll et al., 2010) muscle length changes were estimated based on the knee-hip-joint kinematics during recreational skiing linked with a worst case scenario calculation for differences in muscle tendon unit and fascicle behavior in a closely related movement (Chleboun et al., 2008). Although the average range of motion was about 30°, the estimated length changes were not pronounced enough to explain the changes in mean frequency from the inside leg to the outside leg of RF (mean frequency increase by 16%) and VL (mean frequency increase by 11%) (Kröll et al., 2010). The length changes for the biarticular RF which occur during a 30° knee angle decrease were less than -1% for RF while the length changes for VL were approximately +4% (Kröll et al., 2010). It was found in the current study that the influence of a prolonged skiing session on the knee angle is in general very small and not significant. Hence, the length changes in the current study seem to be negligible for RF and VL.

Consequently, the lower frequency during the POSTskiing for RF and VL cannot be explained by changes in muscle length in the present study. According to the observation by Doud and Walsh (1995) the altered muscle length can account for at least a part of the frequency shift since changes in knee angle were minor.

**Influence of lactate**

Theoretical calculations have shown that the EMG frequency spectrum shifts to higher frequencies as a result of an increase in the motor unit action potential (MUAP) conduction velocity (Lindstrom et al., 1970). Hence, much of the variation in the frequency component of the EMG has been attributed to changes in MUAP conduction velocity. A decrease of pH results in a decrease of MUAP conduction velocity, and as a consequence, a decrease of EMG mean frequency (Brody et al., 1991). As metabolites such as lactates decrease pH it has been suggested that the shift in the EMG spectrum towards lower frequencies during fatigue indicates a close relation to the level of accumulated lactate within the muscle (Horita and Ishiko, 1987, Tesch et al., 1983). The lactate level in the current study differed between PREskiing and POSTskiing, but this level decreased significantly during the prolonged skiing session (Figure 3C). A shift to lower frequencies was observed for the frequency content of the EMG signal due to the prolonged skiing session. This is opposite to what the lactate effect should cause according to Horita and Ishiko (1987) or Tesch and Komi (1983). For this reason we consider that lactate changes were not responsible for the observed changes in the intensity spectrum seen here.

**Influence of muscle temperature**

Next to altered muscle length or altered metabolites some of the variation in EMG frequency may be due to differences in the temperature of the muscle. The conduction velocity of nerve and muscle action potentials is a function of tissue temperature. It increases by ~5% per degree C as the temperature of the nerve increases from 29° to 38° (Kiernan et al., 2001). During an isometric contraction of the biceps brachii at different force levels it has been demonstrated that a 10° reduction in temperature results in a 32Hz reduction in centre frequency (Petrofsky and Laymon, 2005). It is therefore suggested to ensure that skin temperature is within defined limits before clinical measurements (Kiernan et al., 2001). In a complex field study like the present skiing study, environmental conditions for testing cannot be absolutely controlled. However a window of acceptable temperatures can be determined as was done in this study. Muscle temperature may vary greatly in an outdoor study due to the influence of previous exercise, clothing, and daily rhythm of environmental temperature. With respect to the previous exercise aspect, an adequate warm up process was completed which included two runs of skiing and a 15min ride on a cycle ergometer. Hence it was assumed that the muscle temperature during the PREskiing runs was similar to that during the prolonged skiing session and POSTskiing. Accordingly, subjects wore current state of the art clothing made of breathable material with the aim of minimizing heat accumulation. The change of environmental temperature due to the daily fluctuation is less pronounced on slopes with a north exposure because of the shadow effect. Consequently a slope with north exposure was selected for the experiment with an additional advantage of consistent snow conditions during the day. Nevertheless a slight increase in environmental temperature during the day occurred and could be assumed that muscle temperature increased slightly compared to the PREskiing situation. An increased muscle temperature would result in increased mean frequency (Kiernan et al., 2001, Petrofsky and Laymon, 2005). Our results depict a shift to lower frequencies due to the prolonged skiing session and this is opposite to what the temperature effect should be. For this reason we consider that increased temperature was not the mechanism underlying the observed changes in the intensity spectrum, but we estimate that if anything, the temperature effect reduced the amount of the observed changes.

**Effect of recruitment patterns**

The pattern of motor unit recruitment is an important factor in shaping the myoelectric intensity spectrum. Action potentials from faster fibers travel at higher conduction velocities and thus have higher mean frequencies, so an EMG frequency spectra provides information about motor unit recruitment strategies (Solomonow et al., 1990). Recently it was shown by theoretical calculations, that recruitment strategies resulting in a greater proportion of faster muscle units...
being active had a significantly higher mean frequency (Wakeling, 2009). Although other physiological factors can bias the EMG frequency, careful experimental and statistical design can account for such bias, and so distinct high- and low- frequency components of the EMG have been reported for a range of in vivo activities (Wakeling and Rozitis, 2004, Wakeling et al., 2006, von Tscharner, 2002). It has been suggested, these spectral characteristics are the result of altered recruitment patterns between different motor units. It does not appear that the changes in myoelectric intensity spectra that occurred during the submaximal skiing session can be explained by the length of the muscle fiber or by the decrease in physiological changes (pH level, muscle temperature). The most plausible explanation for the observed changes in myoelectric signal is that the pattern of motor unit recruitment was altered during the 3 hour skiing session.

In the classical explanation of fatigue, it would be expected that in order to maintain muscle power output required for skiing at a constant pace, more muscle fibers would have to be recruited or that they are excited at higher frequencies as they become fatigued (Wakeling et al., 2001). Fast twitch fibers are more susceptible to fatigue than the slow muscle fibers (Komi and Tesch, 1979, Moritani et al., 1982) and increased recruitment should occur for these fibers in particular. If such a fatigue effect occurs during a prolonged alpine skiing session one could assume that an increased recruitment in high frequencies should be observable along all time windows of a double turn. Figure 5 does not depict such a uniform alteration at higher frequency band. The general decrease in mean frequency combined with inconsistent changes within the time windows is contrary to the assumption, that additional fast fibers are recruited due to the reduced power output of other fibers.

From a physiological point of view those results correspond with findings on glycogen depletion during alpine skiing (Nygaard et al., 1978, Tesch et al., 1978). For most recreational downhill skiers, the major glycogen loss occurs in the slow fibers. This suggests that this fiber type produces the predominant proportion of tension development during a day of alpine skiing (Nygaard et al., 1978). On the other hand highly skilled (racers) and unskilled (beginners) skiers, which were not investigated in our experiment, also showed particular responses on fast fibers (Nygaard et al., 1978). Hence, with respect to our findings and the earlier studies on glycogen depletion we suggest that the fast fibers do not reach a state of fatigue in terms of generally reduced power output as they are not used to a large extend during recreational skiing. This argument is furthermore supported by the results of earlier published isometric peak force data which were not different from PREskiing to POSTskiing (Seifert et al., 2009).

In earlier studies it was also suggested, that glycogen depletion toward the end of the day, especially in the slow fibers, could contribute to the injury pattern which peaks toward the end of the ski day (Seifert et al., 2009). A generally reduced power output of the slow fibers should be reflected in the EMG signal in the way that additional fibers are recruited along the double turn. But similar to the fast components, no uniform alteration along the 10 time windows in the slow frequencies can be observed (Figure 5).

**Altered timing of muscle activity during a prolonged skiing session and implication on functional aspects of the skiing technique**

We suggest that the observed shifts in frequencies towards lower values in the present study are not caused by a general substitution of fibers with a concomitant reduction in power output. The most plausible explanation for the reduced frequencies is altered skiing style with modified timing of muscle activity. Depending on the turning side (inside leg vs. outside leg) different alterations occur and the shift to the lower frequencies in the POSTskiing can be explained in several ways. For example RF on TOP showed a clear decrease of the high frequency components during the earlier phases of the inside leg (Figure 5; time window 2|3). Conversely, a clear increase in the low frequency components specifically can be observed during the last part of the turn on the outside leg for RF (Figure 5; time window 9|10).

This level of detail has been made possible by the use of wavelet analysis on the myoelectric signal. The mean frequency of the power spectrum, calculated by a Fourier transformation, was previously used to evaluate fatigue during alpine skiing (Ushiyama et al., 2005). The results showed a decreasing trend in mean frequencies which appeared to be more pronounced in the afternoon compared to that in the morning. However, a discussion of this shift in frequencies was not possible in terms of an altered timing of muscles (skiing style) due to the collapse in temporal aspects of the signal. Hence, interpretation of these data is limited.

It was shown recently (Kröll et al., 2010) that the functional importance of RF during recreational skiing in the inside leg is very high. From a coordinative point of view, recreational alpine skiers should try to obtain an adequate bilateral loaded skiing technique (Mueller and Schwameder, 2003). To accomplish this, the skier has to shift weight to the inside leg by knee extension, while being careful to avoid too high of loading of the inside leg by hip flexion. The situation dependent repetitive loading (RF as knee extensor) and unloading (RF as hip flexor) activities are crucial and are reflected in the EMG signal by the involvement of more fast twitch fibers throughout the muscle contraction in the inside leg compared to the outside leg (Kröll et al., 2010). After the prolonged skiing session, there was a decrease in high frequency components which could be a result of a reduction in the recruitment of fast components at the TOP and at the END of the run in the inside leg. The corresponding overall EMG intensities decreased on TOP for the inside leg, but increased at the END on the outside leg. Therefore, the situation dependent repetitive loading (RF as knee extensor) and unloading (RF as hip flexor)
activities seem to be reduced and skiers ski more unilaterally on the outside leg. Even though the functional capacity would be enough to maintain the original skiing style, recreational skiers could preferentially ski more unilaterally, on the outside leg, in order to reduce the load on the inside leg. One could speculate that this occurs due to the necessity to have a recovery phase during each inside leg phase.

Following the biomechanical distinction of the carving technique and the traditional parallel technique (Mueller and Schwameder, 2003) we suggest that the prolonged submaximal skiing session leads to a shift in skiing style towards the traditional parallel technique. This alteration in skiing style is furthermore supported by the overall intensity results of VL which changed in the same way as the RF (Table 1). The observation that activity peaks occur later within the turn for almost all situations (in seven cases out of eight, Figure 5), after the prolonged skiing session, is another indicator of a shift to traditional parallel technique since the duration of the initiation phase for the following turn is thereby reduced (Mueller and Schwameder, 2003).

Mueller and Schwameder (2003) suggested when skiers use carving skis with adequate technique, they maintain better sagittal balance and have improved edge steering ability that help them remain centrally positioned over their skis. The enhanced steering ability when using a co-loading technique was recently described by theoretical calculations (Heinrich et al., 2009). Furthermore, an increase in force does not occur as quickly with co-loading as with traditional parallel turn technique (Mueller and Schwameder, 2003). We speculate that the altered skiing style towards the traditional parallel turn counteracts the functional properties of carving skis. This could increase the potential risk for over edging and consequently for falls as the sagittal balance and the edge steering behavior of the equipment is altered. From a skiing safety perspective, the more rapid force increase on the outside leg compared to the bilateral steered (more controlled) technique at the beginning of the skiing session may be important. It seems to be plausible that quicker and more uncontrolled force increases in combination with the self steering abilities of carving skis may increase the risk of potential falls due to sudden, unanticipated edging. We suggest that recreational skiers should be intentionally instructed to maintain a situation dependent repetitive loading (RF as knee extensor) and unloading (RF as hip flexor) activity of the inside leg to reduce the shift towards a traditional parallel technique during a prolonged skiing session.

CONCLUSION AND OUTLOOK FOR OTHER ALPINE SKIING SITUATIONS

Based on our interpretation of these data, we propose that the frequency decrease and intensity changes for RF and VL are caused by altered timing (coordination) within the turn. Furthermore, general muscular fatigue, where additional fibers have to be recruited due to reduced power output of specific motor units, likely does not occur. In other words, these data provide evidence to suggest recreational skiers alter their skiing technique before a potential change in muscle fiber recruitment occurs.

It is important to note that the current study did not employ an extreme exercise, but used a 3 hour skiing session at an intensity which is indicative of recreational skiing. Seifert et al (2005) using slightly longer run times reported similar HR data but greater changes in physiological stress markers compared to the current study. Perhaps the actual methods used, combined with using longer ski durations or greater intensities, might identify general muscle fatigue during skiing in a way that additional specific fibers have to be recruited to prevent a reduction in power output.

For elite competitors in alpine ski racing, investigators reported heart rate (HR) and oxygen consumption (VO2) achieve or exceed maximal values during competitive alpine skiing (Tesch, 1995) and glycogen depletion of fast fibers, in particular, was identified (Nygaard et al., 1978). Hence, for alpine ski racing an increased recruitment could occur in fast twitch fibers since these fibers are susceptible to fatigue (Komi and Tesch, 1979, Moritani et al., 1982). To suggest general muscle fatigue does generally not occur in alpine skiing would exceed the scope of this study, but could be investigated using this same method with more intensive skiing applications (aim for future projects). For the applied prolonged skiing session in recreational skiers in this study the modified skiing style towards a less functional and hence more uncontrolled skiing technique seems to be a key issue with respect to the influence on muscle recruitment.

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REFERENCES


**KEY POINTS**

- The frequency content of the EMG signal shifted in seven out of eight cases significantly towards lower frequencies with highest effects observed for RF
- General muscular fatigue, where additional specific fibers have to be recruited due to the reduced power output of other fibers, did not occur.
- A modified skiing style towards a less functional and hence more uncontrolled skiing technique seems to be a key issue with respect to the influence on muscle recruitment for applied prolonged skiing session.

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The Relationship of Heart Rate and Lactate to Cumulative Muscle Fatigue During Recreational Alpine Skiing

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Abstract

Seifert, J, Kröll, J, and Müller, E. The relationship of heart rate and lactate to cumulative muscle fatigue during recreational alpine skiing. J Strength Cond Res 23(3): 698–704, 2009—Common indices of fatigue may not respond similarly between downhill skiing and other activities because of the influence of factors such as snow conditions, changing terrain, and skiing style. The purpose of this study was to investigate the relationship and predictors of common fatigue indices during downhill skiing. Ten healthy female recreational skiers skied for 3 hours under standardized conditions. Feedback on heart rate (HR) and finishing time were given to each skier at the end of each run to maintain a relatively stable load. A chronic stress score (Cstress) was calculated from creatine kinase (CK), cortisol, and isometric endurance. Finishing times and HR from runs 2, 12, and 24 were similar. Heart rate averaged 82% of HRmax. Heart rate was an insignificant predictor (p = .65) and was poorly correlated (r = 0.16) to Cstress. Blood lactate (LA) was a significant predictor of the Cstress (p = 0.05; r = 0.62). Pre- to postsking peak forces were not different (p = 0.62), but skiers experienced a significant decrease in isometric endurance from 106.1 ± 29.6 to 93.2 ± 24.0 seconds. Endurance decreased by 13%, whereas cortisol and CK increased by 16 and 42%, respectively. Isometric contraction endurance and blood LA were significant predictors of overall stress. Individual compensation mechanisms and skiing style contributed to highly variable responses during skiing. Whereas HR may indicate stress within a given run, it is not a significant indicator of Cstress and fatigue during recreational alpine skiing. However, the cumulative stress variables and LA can be used in field testing of skiers. It is suggested that LA is a practical on-hill marker of chronic stress.

Key Words muscle stress, muscle damage, performance

Introduction

Downhill skiing is an activity enjoyed by millions of people around the world. The number of skiing days increased from 44 to 51 million (+16%) from 1999 through 2004 in Austria (7). The National Ski Areas Association (13) reported that nearly 7 million skiers made 58.9 million visits to ski areas in the United States during the 2005 ski season.

Alpine skiing can be characterized as continuous activity as the skier maneuvers down the slope. It can also be characterized as an intermittent activity within the run because leg muscles contract more during the turn and then have a semirelaxation period between turns. An individual ski run can last anywhere from 1 to 10 minutes or longer. After a run, skiers usually have a 10- to 15-minute recovery period while they ride a chair lift that takes them to the top of a run. On a typical ski day, skiers will ski approximately 3 hours in the morning, take a lunch break, and then ski for 2–3 more hours in the afternoon.

Numerous authors have reported that muscle contraction forces can reach upwards of 100–150% of maximal voluntary contraction when making a turn (2,4,15,24). Szmedra et al. (21) also added that skiers experienced significant levels of muscle ischemia and hypoxia when they completed short radius slalom-type turns. The combined effects of high forces, ischemia, and hypoxia leads to increased muscle stress during skiing, as noted by the increase in creatine kinase (CK) levels. Seifert et al. (18) noted a 93% increase in CK levels in recreational skiers after 3 hours of self-paced skiing.

Heart rate (HR), blood lactate (LA), myoglobin, and cortisol have also been used to assess the acute and overall stress levels of an activity. Krautgasser et al. (6) and Scheiber et al. (17) recently reported on the acute load effects of skiing. These authors reported that recreational skiing results in a blood LA of approximately 2 mmol·L⁻¹. These data support previously reported average blood LA of 2.7 mmol·L⁻¹ in younger (18–45 years old) recreational skiers after 3 hours of self-paced skiing (18). Those authors also reported a skiing HR of approximately 80% maximal of HR.
(HRmax) in older recreational skiers (6,17). In contrast, race training significantly increases skiing HR more than that of recreational skiing. Burtscher et al. (3) reported that HR during controlled giant slalom skiing was approximately 87% HRmax in elite skiers, whereas Seifert et al. (19) reported that elite collegiate racers trained at approximately 97% HRmax during giant slalom training.

With thousands of repeated contractions occurring during a day of skiing, some level of fatigue is inevitable. From a training point of view, it can be argued that a certain amount of fatigue or stress is required to enhance physiological capacity. However, too much fatigue exposes the skier to increased risk of injury and reduces the pleasure of the activity (1,5,9,10,12). Identifying and understanding the physiological responses to fatigue, improvements in the sports equipment used in the activity, changing work to rest ratios of the activity, and using nutritional interventions are helpful in not only improving the comfort and enjoyment of skiing, but also enhancing the training and safety associated with this activity.

It is important to understand how a specific activity can change the various physiological indices associated with fatigue. For example, in activities such as cycling and running, HR and blood LA levels are positively correlated to and good predictors of an acute training load and resulting fatigue. As the training load increases, HR and blood LA also increase (11,20,22). As a result, common fatigue indices and muscular stress increase with increasing training loads. It is not known if HR and blood LA change in a similar manner when skiing because of the influence of external factors, such as snow conditions, changing terrain, and changing ski edge pressure application, all of which increase muscular stress. Little is known about how HR and blood LA levels interact with the indices of muscle stress during recreational skiing.

Therefore, the aim of this study was to investigate if acute load variables, represented by HR and blood LA during alpine skiing, may serve as predictors and correlates of chronic stress, as assessed by the cumulative fatigue indices. Consequently, chronic stress was induced in a group of recreational skiers by requiring them to ski at a consistent manner in standardized skiing conditions.

**METHODS**

**Experimental Approach to the Problem**

Subjects were instructed to refrain from exercise the day before skiing. All subjects arrived the night before testing and slept in a hotel at the resort. Timing was standardized from waking to the beginning of testing. Subjects consumed a standardized breakfast the morning of their test.

**Subjects**

Ten healthy women (age, 22.7 ± 4.0 years) gave informed consent to participate in this study after institutional review board approval. All subjects were healthy, university sport science students who were physically active but not engaged in competitive athletic training. To get a homogenous sample, subjects were selected according to their skiing ability and amount of skiing days per year. All subjects were of the intermediate level based on the Austrian Ski Teaching Concept (23). Intermediate level skiers are able to perform short and long radii turns on prepared terrains. In flat terrain, intermediate skiers are able to execute carved turns but perform mostly skid turns on steep terrain.

All subjects followed a standardized warm-up by completing a 15-minute warm-up ride on a cycle ergometer and 2 warm-up runs on the ski slope. Peak isometric force was measured with a force plate mounted on an upright, stationary seat. The right leg was used for testing with a knee angle of 100 degrees. The right leg was used for testing with a knee angle of 100 degrees. The test was performed with the highest value used for statistical analysis. The protocol was made with 3 seconds to attain peak force with 12 seconds in between attempts. The isometric endurance test was completed 5 minutes after the peak force test was completed. The endurance test was performed at 45–50% of the preskiing maximal isometric force with a knee angle of 100 degrees. The test was terminated when sustained force decreased to less than the 45% of peak force for a total of 1.5 seconds. Peak force and isometric endurance test were measured 10 minutes before and 10 minutes after skiing. Verbal encouragement was not provided to the subjects during these tests. Visual feedback on force output was made available to the subjects; however, they did not receive information on elapsed time during the endurance test.

Data collection occurred at Hinterreit Ski Area in Maria Alm, Austria during the month of March. Each run took approximately 100 seconds to complete. Figure 2 shows each individual skier’s average run times. After the isometric endurance test, muscle fatigue was induced by skiing 24 runs during a 3-hour period. Total ski time for the 24 runs was approximately 40 minutes of the 3 hours total time. Within each run, there were 3 pitch changes: 21, 29, and 13 degrees.

![Figure 1. Heart rate during skiing from 3 individual skiers.](https://example.com/figure1.png)
Subjects performed an average of 22 turns on the 21-degree pitch, 10 turns on the steep pitch, and 28 turns on the flat section. Total elevation change for the run is 300 m vertical elevation, with the bottom of the run at 890 m above sea level. This run is classified as an intermediate level run. Intermediate level runs are classified as moderate difficulty, moderate length, and a moderate level of risk. To control the length of turns and distance skied across the fall line, subjects skied through a standardized corridor on groomed ski terrain. Although they could ski as they preferred, they were instructed to maintain similar finishing times and HR for their individual runs to ensure a standardized load throughout their skiing. To reach this goal, verbal feedback on HR and finishing time were provided to each skier at the end of each run. Skis were standardized according to body size and consisted of 150 or 160 cm recreational slalom skis (Atomic, Inc., Altenmarkt, Austria).

Salivary and earlobe blood samples were collected after breakfast (time 0) and after the 2nd, 12th, and 24th run. Salivary samples were analyzed for cortisol (Diagnostic Products, Inc., Ft. Lauderdale, Fla.), whereas the 20-μL blood samples were analyzed for LA (Biosen 5140; EKF-Diagnostic GmbH, Magdeburg, Germany). An additional blood sample was collected at time 0 and 3 hours after skiing and analyzed by reflectance photometry at 25°C for CK (Reflotron; Roche Diagnostics, Basel, Switzerland).

Heart rate was collected at the end of each run (Polar Electro Oy, Kempele, Finland). Heart rate was not collected at the 13th run to allow subjects a short break to empty their bladder. Percent of HRmax was calculated of 220 by age.

The cumulative stress variables were CK, cortisol, and isometric endurance performance. A chronic stress score (Cstress) was then calculated from how the individual ranked among our group of skiers for the cumulative stress variables. For example, the skier with the greatest percent change in CK received 10 points, the skier with the second largest change received 9 points, and so forth. One goal of the study was to determine the Cstress and compare it to acute load variables. Acute load variables are described as per run loads and include HR and LA.

Statistical Analyses
Data were analyzed with an analysis of variance and t-tests (EXCEL; Microsoft Inc., Redmond, Wash.). All data and figures are expressed as mean ± SD. Alpha level of p ≤ 0.05 was accepted as significant. Regressions and correlations were performed between Cstress and the load variables and between Cstress and chronic stress variables. Analysis was performed on data collected after the 2nd, 12th, and 24th runs. These data are expressed by run number rather than time because skiers completed their run with different finishing times. In a time-point reference, data were collected at approximately 15 minutes (2nd run), 90 minutes (12th run), and 180 minutes (24th run) into skiing.

RESULTS
Figure 1 depicts the HR responses from 3 skiers on a typical ski run cycle. This cycle includes skiing the run in approximately 1:40 minutes, then a slight pause on the hill for the investigators to record data, and then to ski the 20 m to
Average run time for the group from runs 2, 12, and 24 was 101.5 ± 5.5 seconds (Figure 2). The fastest average finishing time for an individual skier for those 3 runs was 95.0 seconds by subjects 6 and 9, whereas subject 8 had the slowest time at 108.7 seconds (Figure 2). Although the between-subjects range was 13.7 seconds, the within-subject range in finishing times was consistent. The average finishing time for all the subjects and all 24 runs was 102.9 ± 7.1 seconds.

The group average for HR during runs 2, 12, and 24 was 166.7 ± 15.5 b.min⁻¹. The 166.7 b.min⁻¹ represents 84.5 ± 77% of estimated HRmax (Figure 2). Skier 5 skied with an average of 68.5 % HRmax over the 3 runs, whereas skier 8 skied with the highest %HRmax at 92.8% (Figure 2). Heart rate was an insignificant predictor (r² = 0.65) and was poorly correlated (r² = 0.03) to the Cstress. Thus, only 3% of the variability in the Cstress could be accounted for by HR. Over the 24 runs, subjects skied at an average of 82.5 ± 8.8% of HRmax.

Average blood LA was 2.7 ± 1.1 mmol.L⁻¹ after the second run (Figure 3). Lactate decreased significantly by the 12th and 24th runs to 1.8 ± 0.7 and 2.0 ± 1.0 mmol.L⁻¹, respectively. Individual LA values ranged from 1.24 to 4.45 mmol.L⁻¹ after the 2nd run and from 0.9 to 3.63 mmol.L⁻¹ after the 24th run (Figure 4). Blood LA was a significant predictor of the Cstress (r² = 0.05) with an r² value of 0.40. Thus, LA accounted for approximately 40% (moderate level) of the variability in the Cstress.

Changes in the first 3 salivary cortisol collections reflect what would be expected in the diurnal changes (Figure 3). Cortisol concentration decreased significantly from the preskiing level to the 12th run (4.5 ± 1.4 to 2.9 ± 0.8) collection point. However, cortisol levels increased significantly by 16% in the final 1.5 hours of skiing. 

Creatine kinase significantly increased during the skiing. The preskiing CK concentration was 40.4 ± 19.3 U.L⁻¹. Three hours after skiing, CK concentration had increased to 57.3 ± 25.4 U.L⁻¹, an increase of 42% (r² = 0.000). Individual CK changes ranged from 1 to 42 U.L⁻¹.

Peak force did not statistically change during the skiing (r² = 0.62). Preskiing peak force was 1151.6 ± 202.1 N compared to the postskiing peak force value of 1112.4 ± 187.7 N. Skiers experienced a significant decrease of 12% in isometric endurance time (r² = 0.02). Preskiing isometric endurance time was 106.1 ± 29.6 seconds, whereas postskiing endurance time was 93.2 ± 24.0 seconds. Eight of 10 skiers experienced a reduction in endurance time performance (the largest individual decrease was 38 seconds), 1 skier had the same time, and 1 skier increased endurance time from before to after skiing by 10 seconds.

Although the variables to calculate chronic stress are dependent variables, a regression was performed to get a sense of how each of the 3 impacted chronic stress. The most important regression variable in assessing this stress was isometric endurance (r² = 0.81), whereas CK had an r² of 0.34, and HR had an r² of 0.02.

### Table 1. Individual skier responses.

<table>
<thead>
<tr>
<th>Subject</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lactate (mM L⁻¹)</td>
<td>3.6</td>
<td>2.8</td>
<td>2.0</td>
<td>2.0</td>
<td>1.8</td>
<td>1.4</td>
<td>1.5</td>
<td>1.0</td>
<td>3.6</td>
<td>1.9</td>
</tr>
<tr>
<td>%HRmax</td>
<td>86</td>
<td>90</td>
<td>85</td>
<td>92</td>
<td>69</td>
<td>85</td>
<td>87</td>
<td>93</td>
<td>74</td>
<td>86</td>
</tr>
<tr>
<td>% Time lost</td>
<td>−30.6</td>
<td>−8.5</td>
<td>1.1</td>
<td>−22.8</td>
<td>−13.3</td>
<td>−19.8</td>
<td>0.0</td>
<td>−4.0</td>
<td>−17.4</td>
<td>7.9</td>
</tr>
<tr>
<td>% CK</td>
<td>101.6</td>
<td>54.2</td>
<td>105.8</td>
<td>32.8</td>
<td>2.2</td>
<td>50.0</td>
<td>37.9</td>
<td>12.4</td>
<td>91.3</td>
<td>22.2</td>
</tr>
<tr>
<td>% Cortisol</td>
<td>91.7</td>
<td>−29.8</td>
<td>−7.3</td>
<td>31.8</td>
<td>25.0</td>
<td>25.1</td>
<td>10.7</td>
<td>18.3</td>
<td>40.5</td>
<td>18.7</td>
</tr>
<tr>
<td>Cumulative stress</td>
<td>27</td>
<td>13</td>
<td>14</td>
<td>22</td>
<td>13</td>
<td>21</td>
<td>11</td>
<td>12</td>
<td>25</td>
<td>9</td>
</tr>
</tbody>
</table>

%HRmax = Percent of maximal heart rate; % Time lost = Percent time lost in isometric contraction endurance test; % CK = Percent change in creatine kinase from pretest to 3 hours after run 24; % Cortisol = Percent change in cortisol from run 12 to 24; Cumulative stress: Chronic stress score from ranking in CK, cortisol, and isometric contraction test results.

Lactate, CK, and HR data were taken from runs 2, 12, and 24.

The lift house, riding the 4:30 minute ski lift to the top of the run, and preparing to execute the run.

Average run time for the group from runs 2, 12, and 24 was 101.5 ± 5.5 seconds (Figure 2). The fastest average finishing time for an individual skier for those 3 runs was 95.0 seconds by subjects 6 and 9, whereas subject 8 had the slowest time at 108.7 seconds (Figure 2). Although the between-subjects range was 13.7 seconds, the within-subject range in finishing times was consistent. The average finishing time for all the subjects and all 24 runs was 102.9 ± 7.1 seconds.

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Changes in the first 3 salivary cortisol collections reflect what would be expected in the diurnal changes (Figure 3). Cortisol concentration decreased significantly from the preskiing level to the 12th run (4.5 ± 1.4 to 2.9 ± 0.8) collection point. However, cortisol levels increased significantly by 16% in the final 1.5 hours of skiing. 

Creatine kinase significantly increased during the skiing. The preskiing CK concentration was 40.4 ± 19.3 U.L⁻¹. Three hours after skiing, CK concentration had increased to 57.3 ± 25.4 U.L⁻¹, an increase of 42% (r² = 0.000). Individual CK changes ranged from 1 to 42 U.L⁻¹.

Peak force did not statistically change during the skiing (r² = 0.62). Preskiing peak force was 1151.6 ± 202.1 N compared to the postskiing peak force value of 1112.4 ± 187.7 N. Skiers experienced a significant decrease of 12% in isometric endurance time (r² = 0.02). Preskiing isometric endurance time was 106.1 ± 29.6 seconds, whereas postskiing endurance time was 93.2 ± 24.0 seconds. Eight of 10 skiers experienced a reduction in endurance time performance (the largest individual decrease was 38 seconds), 1 skier had the same time, and 1 skier increased endurance time from before to after skiing by 10 seconds.

Although the variables to calculate chronic stress are dependent variables, a regression was performed to get a sense of how each of the 3 impacted chronic stress. The most important regression variable in assessing this stress was isometric endurance (r² = 0.81), whereas CK had an r² of 0.34, and HR had an r² of 0.02.
and salivary cortisol was at 0.32. The regression formula for cumulative stress was chronic stress = 8.021 ± 0.337 (change in isometric time) + 0.072 (percent change CK) + 0.085 (percent change cortisol) (p = 0.000; r² = 0.961).

**DISCUSSION**

The aim of this study was to investigate how well the acute markers of stress, HR and LA, predict and correlate with chronic stress when skiing at a recreational level intensity. This study did not use an extreme exercise but a half-day session of skiing at an intensity that is indicative of recreational skiing. The importance of this study was to assess the viability of typical field measures of LA and HR in predicting chronic stress.

We used a novel approach of assessing stress during skiing. The cumulative stress variables, isometric contraction time, CK, and cortisol were used to calculate a chronic fatigue score. These markers were used because each one would not change appreciably over a single run. In contrast, HR and LA were used as acute markers because these variables are frequently used and could change from run to run.

Isometric contraction performance time was the most important single factor in the regression equation accounting for 82% of the variance in the Cstress, whereas CK and salivary cortisol were moderate factors in accounting for 34 and 32% of the variance in Cstress, respectively. Based on the changes of the selected measures, LA was a significant predictor of and correlated with chronic stress. However, HR was not a significant predictor and did not correlate with chronic stress during skiing. We postulate that HR is not sensitive to overall fatigue because of the influence of multiple factors during skiing.

Environmental and mechanical factors exert a profound influence in the physiological responses to skiing intensity. For example, the environmental factors of snow conditions and changing terrain may force the skier to alter their skiing style accordingly. An individual's fitness level and skiing style, such as ski edge angulation during a turn, changing pressure distribution to the ski edge, intensity and type of muscle contraction (or efficiency of movement), and turn radii affect acute physiological responses, and hence, muscle stress. We controlled for snow conditions by having skiers ski a groomed course in similar temperatures. Turn radii were controlled by skiers completing turns within a standard corridor, skis were waxed each day, and skiers were of similar skiing ability. Although we controlled run time and HR during skiing, skiers could still change edge angles, pressure distribution on the ski, and muscle contraction mechanisms based on their individual style and preferences.

As the data demonstrate, individual ski styles leads to variability in the skiers' physiological responses (Table 1). Verbal feedback was given to the skiers to ski consistently from run to run. Although finishing times were approximately 103 seconds, the range of physiological responses in that subjects skied to achieve this time was substantial (Figure 2). Skier 8 demonstrated a low Cstress, achieving a HRmax at 93%, a very low LA of approximately 1.0 mM L⁻¹, finished the runs with an average time of 102 seconds, possessed a small change in CK, and lost 4 seconds in the isometric endurance test. By comparison, skier 1 demonstrated a high level of stress with the highest LA, lost the most time in the endurance test at 38 seconds, had an average run time of 105 seconds, had a large increase in CK, and skied at a HRmax of 86%. Subject 9 also had a high Cstress, as noted by an increase in LA, losing 19 seconds in the endurance test, had an average finishing time of 97 seconds, had a large increase in CK, and skied at an average percent of HRmax of 74%. Although the between-subject range of these variables was substantial, the within-subject range in the data over the 24 runs was rather small but consistent.

Blood LA and HR are frequently used indicators of fatigue and muscle stress during physical activity. Using these two criteria, recreational skiers often select skiing intensities that are moderate in nature. Average LA during skiing in the present study was approximately 2 mmol L⁻¹, similar to what was has been reported previously (6,17) and slightly less than what Seifert et al. (18) reported (2.7 mmol L⁻¹ vs. 2.0 mmol L⁻¹).

The dichotomy between LA and HR in the present study may arise from changing pace within the turn or different skiing styles. The change in pace occurs when performing a turn simply by changing edge angle and edge pressure, having to respond to variable snow conditions, such as hard pack vs. soft snow, and responding to changes in terrain or pitches. Thus, there are many options to change the steering variables within a turn, and consequently, the physiological responses will change accordingly. Changing the variables is difficult in activities such as cycling and running where HR and LA are acceptable indicators of acute stress and fatigue.

It is interesting to observe the 30% decrease in average LA from run 2 to 12, after only 1.5 hours on snow (20 minutes of actual skiing) and then little change in LA from run 12 to 24. We cannot explain why this occurred, given that HR and time to complete each run was held relatively constant. It is possible that skiers changed their style or pace of skiing to make sure they could make all 24 runs, using more of the terrain to aid in steering, changing edge angles or pressure distribution of the skies, or a change in muscle recruitment patterns to use more type I muscle.

Kröll et al. (7) reported a distinct shift in mean power frequency, indicating a change in fiber recruitment patterns during skiing-induced fatigue. These authors reported a shift from a predominant signal of fast twitch frequencies (IIa) to a signal dominated by slow twitch frequencies in the vastus lateralis because this muscle fatigues. These findings support those of Sadoyama and Miyano (16) who noted a shift from type II fibers to type I during fatigue. The consistently low LA levels in the last 12 runs in the present study, along with Kröll et al.’s (7) findings, indicate that there is a preferential
recruitment pattern toward the type I muscle fiber as fatigue occurs during recreational skiing.

There are different ways that fatigue may be manifested during skiing. Consequently, the indices to assess fatigue may vary in response to the method used to induce muscular fatigue. Whereas total vertical meters skied in the present study was similar to that reported by Seifert et al. (18), the type, or severity, of muscular stress seems to be different. Skiers averaged approximately 103 seconds per run in the present study, whereas run times were approximately 5 minutes in the Seifert et al. (18). Vertical meters per run and, consequently, time per run was quite different between the 2 reports. The run time difference may have implications on the type of metabolic and contraction requirements placed on the active muscles.

Skiing is an activity with a high degree of eccentric muscle contraction (2). Skiers may experience increased levels of stress and muscle damage on a longer vs. a shorter run. Seifert et al. (18) noted a significant increase in CK of approximately 93% (from 126 to 243 U L⁻¹) in a group of recreational skiers. Creatine kinase concentration increased by an average of 42%, from 40 to 53 U L⁻¹, in the present study.

The apparent disparity in CK concentration between the present study and Seifert et al.'s (18) may be explained by differing CK analysis methods (Reflotron® vs. Johnson & Johnson Vitros II®; Johnson and Johnson, Langhorne, Pa.) or, most likely, that skiers skied twice as many runs (24 vs. 12) but less vertical distance per run in the present study (300 vs. 600 vertical meters). With less vertical skiing per run in the present study, the active muscles may have been subjected to less contractile stress during any run. Given the fact that the lift time was approximately 5 minutes, there may have been enough time to recover between runs. It also stands to reason that contractile stress in the muscle was less per run in the present study. Thus, it may have been the combined effect of a run time with recovery on the lift that contributed to the apparent CK difference in the 2 studies.

It is well known that salivary cortisol is an indicator of stress and follows a circadian rhythm throughout the day. As physical stress increases, so does salivary cortisol concentration (8,14). Under normal, unstressed conditions, cortisol typically reaches a peak during the early morning hours and then progressively decreases throughout the day to reach a nadir sometime around midnight. Although we did not collect 24-hour samples from our subjects, the assumption is that cortisol would have continued to decrease under resting conditions. O'Connor and Corrigan (14) reported salivary cortisol levels increased after 30 minutes of continuous cycling at 75% maximum oxygen uptake. However, cortisol levels decreased with time during the resting control trial in that study. Cortisol increased by 16% from the 12th to the 24th run (approximately 1.5 hours on the hill and 18 minutes of actual skiing) as skiers fatigued in the present study. The lower intensity of exercise and short duration of the runs (approximately 100 seconds) would explain why the magnitude of change is less in the present study than other reports. These results indicate that cortisol did increase under stress, that it could be used as training aid, or to aid future studies in fatigue and stress.

**Practical Application**

Skiing is an atypical sport where many external and internal variables act upon the skier. Individual compensation mechanisms and skiing style contributed to highly variable responses during skiing. It is important for the practitioner to be able to discern acute from chronic stress in terms of physiological responses, especially in sports such as downhill skiing. Measuring only one variable of stress may not be indicative of the true stress of the activity. Whereas HR is an indicator of acute stress within a given run, it was not a good indicator of chronic stress and fatigue. The use of LA as a practical on-hill marker of chronic stress is, however, Blood LA should be measured to assess skiing load. This information can help the instructor, guide, or coach give direction to the skier regarding skiing intensity to minimize chronic stress. This may be particularly helpful during multiday skiing.

When the results of the present study and Seifert et al. (18) are compared, it seems that intermediate level skiers should ski shorter runs to minimize muscle stress and optimize recovery on the chair lift. The present study’s results indicate that skiers don’t feel as fatigued with shorter runs; however, objective data indicate that fatigue and stress still occurred. Future research may include the training effect of alpine skiing and identifying proper training zones for skiing. From a safety perspective, physical preparation for skiing should not neglect, and possibly emphasize, type I muscle fiber development because this is the fiber the body relies on during muscular fatigue and improving the methods of quantifying overall stress during different types of interventions (dietary manipulation, materials, etc.). With this knowledge, determining training loads for positive physiological adaptations and minimizing negative stressors that may lead to greater enjoyment of skiing and improved safety is required.

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**References**


Fatigue During Skiing


Summary, Overall Conclusions and Perspectives

Methodological point of view
(Wavelet analysis for alpine skiing EMG measures)

For the first aim of this PhD project (see page 14) the following key message can be stated:

- The wavelet analysis method is a powerful tool to describe muscular activity for alpine skiing in a more in depth manner. Substantial conclusions for alpine skiing were (and can be in future) drawn by the analysis of the frequency content.
- Additional physiological and kinematic measures are important to adequately discuss the pattern of motor unit recruitment within a muscle (fast & slow fibres).

In this project, the myoelectric activities were resolved by wavelet analysis into their intensities and frequency in time. This level of detail has been made possible by using wavelet analysis on the myoelectric signals, which would not have been resolvable by root mean square (RMS) or Fourier transformation techniques alone (Wakeling et al., 2001a). The advantage of wavelet analysis is that time resolution in both intensity and frequency is virtually unaffected. The total EMG intensity (PhD Part 1, MSSE Article, Kröll et al., 2010) and the PC I loading score (PhD Part 2, JSSM Article, Kröll et al. 2011) as a measure of the intensity can be seen as an equivalent of the RMS values of traditional EMG amplitude analysis. The mean frequency (MF, PhD Part 1) and the angleθ (PhD Part 2), used in the two project parts are comparable to the mean power frequency from a Fourier transformed signal used to measure EMG frequency content in several studies (MacIsaac et al., 2001). However, the Fourier transformation requires stationary signal behavior during a substantial time span (200 ms, von Tscharner, 2002) and causes a collapse in the temporal aspect of the signal.

With the wavelet transformation used in this project, the investigator has the possibility to define the reduction of data in time space. To describe our results, the information was reduced in time space in two different ways: first, into inside leg and outside leg; and second into 10 equal time windows (time windows 1–10). These two methods seem to be an ideal compromise between holding time information and the possibility of summarizing the information for statistical calculations (Berg et al., 1995).

Although the focus of the present work was to identify general patterns in muscle activity during recreational skiing, a considerable range in inter individual variations was observed too. It was possible to show very individual patterns in both intensity and frequency space. Hence, next to investigations on groups, this method also seems to be a useful tool in quantifying individual skiing strategies/techniques for alpine ski racers. Such evaluations
could be useful in terms of individual performance enhancement of high level ski racers and shows a possible direct practical application out of this PhD project.

Figure 4: Average EMG intensity and mean frequency trace during a double turn (time windows 1–5 = inside leg, time windows 6–10 = outside leg) for the group (+SE) in the steep inclination. A, Relative intensity of m. vastus lateralis (VL). B, Relative intensity of m. rectus femoris (RF). C, Mean frequency of VL. D, Mean frequency of RF.

Presuming that it wouldn’t have been counted for the frequency content, and performed a method for intensity analysis over time only, substantial results would not have been achievable. Figure 4 shows the course of EMG intensities (A, B) and mean frequency (C, D) of the studied muscle from time window 1 to time window 10. Comparing m. vastus lateralis and m. rectus femoris differences in timing, EMG intensity and mean frequency can be observed. The m. vastus lateralis has a plateau-type response in a low level of activity from time window 2 to time window 5 (inside leg). Activity increases to maximum EMG intensities during time windows 7–8 when the right leg is the outside leg. Activity then decreases afterward (Figure 4A). In contrast, m. rectus femoris shows a biphasic activity pattern with two clear maximal periods, one from the inside leg (time window 3) and one from the outside leg (time window 8). Low activity patterns occur during edge changing from inside leg to outside leg (time windows 5–6). The course of m. vastus lateralis mean frequency shows a continuous increase in the inside leg (time windows 1–5) followed by a plateau in the outside leg (time windows 6–10; Figure 4C). In contrast, the result of m. rectus
femoris clearly indicates a more pronounced involvement of higher frequencies in the inside leg compared with the outside leg. The course of m. rectus femoris mean frequencies indicates a plateau both in the inside and outside leg (Figure 4D).

The example above depicts that different muscles show very distinct frequency features among a double turn which are clearly not linked directly to the intensities. Hence, the frequency domain provides muscle functional information not possible from simple intensity analysis. The significance of a frequency analysis was also shown within the fatigue part of the Project. Evaluating the effect sizes $\eta^2$ among the statistical tests (Table 1, PhD Part 2, JSSM Article, Kröll et al. 2011) one can easily identify higher effects for the frequency measures (angle $\theta$) compared to the intensity measures (PC 1 Loading). This means that frequency parameters are more susceptible to identify statistical relevant differences even with lower numbers of subject which will most likely be the case for future alpine skiing research.

The pattern of motor unit recruitment is an important factor in shaping the myoelectric intensity spectrum. Motor unit action potentials show substantial (two to threefold) variations in both conduction velocity and shape between fast and slow-fibre types (Hodson-Tole and Wakeling, 2009). Action potentials from faster fibres travel at higher conduction velocities and thus have higher mean frequencies, so the EMG frequency spectra provide information about motor unit recruitment strategies (Solomonow et al., 1990). The observation of different spectral frequencies at similar EMG intensities is an indicator that different populations of motor units are being recruited for different trials and have previously been reported for running (Wakeling, 2004). However, different spectral frequencies cannot automatically be attributed to changes in pattern of motor unit recruitment. There are different properties of muscle activation, that shape the myoelectric frequency spectrum too (Wakeling et al., 2001a). However, to interpret EMG records, possible mechanisms have to be discussed, with particular focus on whether these can explain the changes in frequencies that were measured in a study. This project considered aspects like the influence of lactate (Lactate↑, EMG frequency↓, Brody et al., 1991)), muscle temperature (Temperature↑, EMG frequency↑, Petrofsky and Laymon, 2005), muscle length (Muscle length↓, EMG frequency↑, Doud and Walsh, 1995) as factors which can shape the conduction velocity of motor unit action potentials. Only if these factors were not able to explain differences in frequencies, was altered recruitment taken into account.

An example how lactate was considered serves the interpretation of the fatigue experiment. The lactate level in the current project (PhD Part 2, JSSM Article, Kröll et al. 2011) differed
between PREskiing and POSTskiing. Mean Lactate level decreased significantly during the prolonged skiing session. A shift to lower frequencies was also observed for the frequency content of the EMG signal due to the prolonged skiing session. This is opposite to what the lactate effect should cause according to Horita and Ishiko (1987) or Tesch and Komi (1983). For this reason it is considered that lactate changes were not responsible for the observed changes in the intensity spectrum seen here; but, it was assumed that if anything, the lactate effect reduced the amount of the observed changes.

Another example for interpreting frequency differences in a complex manner is for instance the differences between m. rectus femoris frequencies on inside leg and outside leg from Figure 4D. The inside leg shows significantly higher frequencies compared to the outside leg. Blood lactate and muscle temperature in this case were not considered since within each double turn, these parameters would not change (too short of a time span). Different muscle length in contrast have to be considered since the knee angle and hip angle are completely different between inside leg and outside leg. Therefore a model based estimation of the muscle length for m. rectus femoris with real kinematic skiing data of hip and knee angle was performed. The model predicted that m. rectus femoris was at nearly constant length throughout the double turn, due to its biarticularity. Hence, next to lactate and muscle temperature, muscle length changes cannot be primarily responsible for frequency differences between inside leg and outside leg. Therefore, the most plausible explanation for the observed differences in the m. rectus femoris myoelectric signal between the inside leg and the outside leg is that the pattern of motor unit recruitment is different. It seems that m. rectus femoris recruits essentially more fast fibres in the inside leg compared to the outside leg.

In conclusion, the used wavelet analysis method is a powerful tool for describing muscular activity for alpine skiing in a more in depth manner. Next to investigations on groups, like shown for the current project, this method is also a useful tool in quantifying individual skiing strategies/techniques among competitive skiers which serves an interesting perspective for further research. However, planning studies using the presented method has to include physiological and kinematic measures to discuss the EMG records in an appropriate way as shown exemplarily above. Not only the usage of the wavelet method alone improves the explanatory power of EMG measures, it has to be embedded into appropriate overall experimental designs. Our experimental approach seems to be adequate. Even so kinetic measurements would improve the possibility to discuss EMG records from a functional perspective. Furthermore the estimation of length changes within the muscle would be improved through kinetic measures. To estimate muscle fibre length behavior from
observation of joint performance alone (kinematic measures), as done for this project, is difficult because fascicles do not behave exactly like the experimental muscle tendon unit. Hence, it is suggested to add kinetic measures (at least in form of case reports, if the efforts are too high to do it for an overall group) for future research on muscle activity in alpine skiing.

Recreational alpine skiing point of view

For the second and third aims of this PhD project (see page 14) the following key statements can be stated:

- Contrary to previously suggested co-loading of the inside leg while carving our results does not support this hypothesis.
- Functional importance of m. rectus femoris: The ability of a situation-dependent loading (m. rectus femoris as knee extensor) and unloading (m. rectus femoris as hip flexor) of the inside leg seems to be a crucial point for recreation skiers.
- The slope inclination is a discriminating factor for muscular activity in recreational alpine skiing. The m. vastus lateralis and m. rectus femoris responded with higher EMG intensities to increased inclinations for both, inside leg and outside leg. The m. vastus lateralis increase was distinctly smaller.
- General muscular fatigue, where additional specific fibres have to be recruited due to the reduced power output of other fibres, did not occur.
- A modified skiing style towards a less functional and hence more uncontrolled skiing technique seems to be a key issue with respect to the influence on muscle recruitment for an applied prolonged skiing session.

The generally accepted notion of a predominantly unilateral use of the one-joint knee extensors during alpine skiing which was stated by Berg at al. (1995), had to be revised with the introduction of the carving skis. Mueller and Schwameder (2003) found in their comparative technique analysis between traditional parallel technique and the carving technique, that in a traditional parallel turn the predominate load is on the outer ski (outside leg) whereas intensive co-loading of the inside leg is found in all turning phases with the carving technique. However, those results were shown with expert level skiers and it was not clear prior this PhD project if those characteristics of skiing technique are evident among recreational skiers. Although, our skiers performed a modern recreational carving technique, the muscle activity results did not correspond with the results for carving technique by Müller and Schwameder (2003). A predominant unilateral use (during the outside leg phase) of the one joint knee extensor m. vastus lateralis seems to occur (Figure 4A). This means that a pronounced co-loading of the inside leg does not occur. In contrast to m. vastus lateralis a
clear biphasic pattern for the two joint m. rectus femoris was observed (Figure 4B). Within the discussion of the functional aspect of the quadriceps muscles (PhD Part 1, MSSE Article, Kröll et al., 2010) a functional extension of m. rectus femoris was described. It is assumed, that m. rectus femoris can also act as a knee extensor on IL, compared to the single hip flexor function described by Berg et al (1995). This argument is based on data prior to the study from Mueller and Schwameder (2003) who reported a change in skiing technique due to the usage of carving skis. It is now realistic to say there is currently a situation dependent loading (m. rectus femoris as knee extensor) and unloading (m. rectus femoris as hip flexor) necessary which is reflected in the EMG activity. Therefore, it can be suggested that the demand is very high for m. rectus femoris during the inside leg phase of recreational skiing. From a coordinative point of view, recreational alpine skiers could thereby obtain an adequate bilateral loaded skiing technique when the inside leg begins to extend the knee, but also be able to avoid too high of a loading on the inside leg when flexing the hip. A potential consequence of high loading on the inside leg is a fall due to over edging.

Assuming the assumptions about the m. rectus femoris are accurate, the demand on m. rectus femoris is greater compared to m. vastus lateralis. A greater demand on m. rectus femoris was shown in other parts of the project too. The influence of inclinations depicts for instance that both muscles responded with higher EMG intensities to increased inclination. For the outside leg, substantial differences between the flat and the steep segments were observed for m. rectus femoris (+150%) and m. vastus lateralis (+119%). For the inside leg, only m. rectus femoris (+93%) showed a substantial increase, whereas the m. vastus lateralis (38%) increase was distinctly smaller. Hence, m. rectus femoris responded on both turn sides much more than m. vastus lateralis which is again an indication of the functional importance of m. rectus femoris. Another indicator for the functional importance of m. rectus femoris is provided by the results from the fatigue part of the PhD project. After the prolonged skiing session, overall EMG intensities decreased on top of the run for the inside leg, but increased at the end of the run on the outside leg. The corresponding effect sizes indicate more pronounced effects on the m. rectus femoris compared to the m. vastus lateralis which again fits in line with the above discussed higher functional demands on the m. rectus femoris muscles. Therefore, the situation dependent repetitive loading (RF as knee extensor) and unloading (RF as hip flexor) activities seem to be reduced with upcoming fatigue, and skiers ski more unilaterally on the outside leg.
Based on the interpretation of the results of the fatigue experiment it was suggested that general muscular fatigue did not occur during the applied skiing session. This paragraph summarizes the interpretation which led to this statement. In the classical explanation of fatigue, it would be expected that in order to maintain muscle power output required for skiing at a constant pace, additional muscle fibres would have to be recruited or that they are excited at higher frequencies as they become fatigued (Wakeling et al., 2001a). Fast twitch fibres are in general more susceptible to fatigue than slow muscle fibres (Komi and Tesch, 1979, Moritani et al., 1982) and increased recruitment should occur for fast twitch fibres in particular if they reach a state of reduced power output. Considering older studies on recreational alpine skiing, it was suggested that from a physiological point of view the major loss of muscle fibres occurs in the slow fibres (Nygaard et al., 1978, Tesch et al., 1978). This suggests that slow fibre types produce the predominant proportion of tension development during a day of alpine skiing and should therefore reduce the power output prior the fast fibres. If this assumption is correct increased recruitment should occur for slow fibres in particular. However, it was not that clear which fibres should be expected to show a changed recruitment in our study. To identify whether in fast or slow fibres a fatigue effect occurs during a prolonged alpine skiing session an increased recruitment in high or low frequencies should be observable along all time windows of a double turn. The data for the fatigue experiment do not depict such uniform alterations at one of the frequency bands, although a general decrease in mean frequency was observed. It was suggested that the observed shifts in frequencies towards lower values in the present study are not caused by a general substitution of fibres with a concomitant reduction in power output. The most plausible explanation for the reduced frequencies is altered skiing style with modified timing of muscle activity.

The shift towards a more unilaterally, outside leg dominated skiing technique was another key piece of information to come from the fatigue experiment. Following the biomechanical distinction of the carving technique and the traditional parallel technique (Müller and Schwameder, 2003) it is suggested that prolonged sub maximal skiing leads to a shift in skiing style towards the traditional parallel technique. The observation that activity peaks occur later within the turn was another indicator of a shift to traditional parallel technique since the duration of the initiation phase for the following turn is thereby reduced (Müller and Schwameder, 2003). From a skiing safety perspective, the more rapid force increase on the outside leg compared to the bilateral steered (more controlled) technique at the beginning of the skiing session may be important. It seems to be plausible that quicker and more
uncontrolled force increases in combination with the self steering abilities of carving skis may increase the risk of potential falls due to sudden, unanticipated edging. It is suggest that recreational skiers should be intentionally instructed to maintain a situation dependent repetitive loading (m. rectus femoris as knee extensor) and unloading (m. rectus femoris as hip flexor) activity of the inside leg to reduce the shift towards a traditional parallel technique during a prolonged skiing session.

Even though not a direct aim of this PhD project the considerations of length changes, originally performed for appropriate interpretation of the EMG records (see previous chapter), serves some aspects which should be considered for future alpine skiing research. Changes in muscle length with respect to concentric versus eccentric muscle contraction have already been discussed (Berg and Eiken, 1999, Berg et al., 1995). Up to now the predominance of eccentric muscle activity has been seen as the unique feature of alpine skiing, and is still the state of the art argument concerning the type of muscle contraction that dominates alpine skiing scientific literature (e.g.: Ferguson, 2010, Gross et al., 2010, Patterson et al., 2009, Scheiber et al., 2010, Tomazin et al., 2008, Turnbull et al., 2009). Berg et al. (1995) interpreted muscle fibre behavior solely from the observation of joint kinematics. This is rather problematic, since the fascicle does not behave exactly like the muscle tendon unit (Ishikawa et al., 2003). Fukunaga et al. (2001) investigated for instance in vivo length changes of fascicles and the tendon of the human m. gastrocnemius medialis during walking (real time ultrasound scanning). They showed that fascicles followed a different length-change pattern from those of the musculotendon complex and tendon throughout the step cycle. The muscle contracted near isometrically in the stance phase and the lengthening of the muscolotendon was achieved primarily by a tendon stretch. In this case the observation of the joint would indicate eccentric muscle contraction mode but the “In vivo mode” was isometric. Coming back to alpine skiing, this means that the predominance of eccentric muscle activity has to be reconsidered. The model based estimation and a comparison with a full squat calculation within this PhD project show clearly that for m. rectus femoris in general and for m. vastus lateralis on the outside leg a dominance of quasi static muscle activity is presumable. Only for m. vastus lateralis a clear eccentric phase on inside leg can be assumed, but the occurring EMG intensity was comparatively low in this phase and hence has minor significance.

By reconsidering the predominance of eccentric muscle activity during alpine skiing, one could therefore deduce specific and practical implications when preparing conditioning
programs for alpine skiers. Thus, during preparation training, isometric strength training content could increase the strength gains because of a residual angle (fiber length) specificity effect and the greater absolute torque involved with isometric training (Folland et al., 2005). However, at the moment the types of contractions are still on a speculative level. To get a more precise picture of the types of contraction that occur during alpine skiing it would make sense to evaluate fascicle length changes via portable real time ultrasound scanning. Even though the method is not easy to use (especially under dynamic conditions) efforts towards in vivo fascicle measures during alpine skiing would make sense and could be one plausible next research direction in combination with the used EMG methods presented in this PhD project.
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