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Influence of Muscular Fatigue on Skiing Performance during Parallel Turns

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***Abstract*—Muscular fatigue and muscle-activation patterns during a skiing demonstration (down a coarse around 4000 m long) was evaluated. Nine subjects participated in skiing trials and pre-training with a squat exercise. Surface electromyogram (SEMG) signals from the agonist and antagonist muscles around the knee at certain knee-joint angles were recorded. The SEMG signals showed that experienced skiers maintained their posture regardless of muscle fatigue by means of sustained muscle contractions in accordance with the change in inclination of the slope. In contrast, intermediate skiers did not maintain their posture (because of muscle fatigue) and distributed their strength over muscles to co-contract with each other. It is concluded from this result that the influence of muscle fatigue on skiing performance is related to skill level.**[1]

I. INTRODUCTION

Currently, so-called "carving skis" have become popular because they allow easy control of turns. A carving ski, however, requires more muscle strength than a conventional ski. The purpose of this study is to evaluate the presence of muscle fatigue during repetitive skiing turns and the influence of muscle fatigue on performance. The performance of a skier depends on his or her skill in controlling muscle contractions according to topographic variations of the slope, and the appropriate skills require training and enough muscle strength. On-site feedback of information concerning muscle activity is thus preferable for evidence-based coaching and for acquiring skill in controlling muscle fatigue.

Researchers have studied muscle activity and motor control evaluated from surface-electromyogram (SEMG) signals in relation to skiing styles such as slalom and parallel turns. The averaged rectified value (ARV) in the amplitude domain and the mean power frequency (MPF) in the frequency domain are typical indices of muscle activity. During an isometric sustained contraction, ARV increases until the contractile-failure point and then decreases, whereas MPF exponentially decreases from the beginning of the contraction [1], [2]. During dynamic knee extension exercise, the similar behaviors of SEMGs were observed of quadriceps femoris, and dominance of the vastus lateralis (VL) occurred in relation to muscular fatigue [3]. Since the skiing consists of dynamic knee extension and flexion, indices of muscle activity, even those during repetitive muscle contractions, should be properly estimated. It is, however, hard to evaluate muscle-activity indices by conventional approaches such as short-term block sliding in time; such approaches also incur very high computational cost. Given these issues, the authors previously proposed a method for measuring and evaluating muscle activity during each turn in real-time on the ski slope [4]. This approach revealed an explicit change in performance due to muscle fatigue during skiing. To evaluate skiing performance, it is thus necessary to select suitable muscles for evaluation.

To analyze eccentric and concentric muscle actions during each turn, Berg *et al.,* [5] measured SEMG signals of knee extensors and hip- and knee-joint angles of skiers during a giant slalom race with a portable tape recorder with sensors. They evaluated EMG activities of the quadriceps in terms of "percentage maximum voluntary contraction" (%MVC) and demonstrated the dominance of eccentric muscle over concentric muscle actions. They also studied performance of elite skiers and revealed slower eccentric muscle actions in the high-speed disciplines like the downhill. Hintermeister *et al.* [6] compared muscle activity in wedge-, parallel-, and giant-slalom ski turns for 12 muscles. Evaluating the root mean squares (RMS) of SEMG signals and the duration of each turn, they showed a difference in the average amplitude for dominant muscles and a difference in the turn durations for each skiing style. SEMG signals were monitored *via* telemetry with a transmitter throughout a skiing course, approximately 100 m long. Clarys *et al.* [7] studied the influence of geographic variations on muscle activity by using an integrated EMG (IEMG) during alpine skiing and cycling. They measured SEMG signals with a transmitter during skiing and cycling. They showed the close relationship between IEMG and the inclination of slopes. Concerning this result, they emphasized the influence of geography on the muscular intensity of the skiing or cycling performance. Nilsson *et al.* [8] measured SEMG signals during telemark skiing with a specially designed lightweight microprocessor carried by the subject over a 186-m-long course. They also examined muscle activities during barbell squats as a training reference of telemark-skiing exercises. They used angular displacement of the knee for analyzing EMG-activation durations and mean EMG amplitudes in flexion and extension phases. Recently, Ushiyama *et al.* [4] used a wearable unit to monitor SEMG signals during parallel skiing over a distance of around 4000 m. Using the knee-joint angles (KJAs) of the inside and outside legs, they focused on muscle activity during each turn. They showed

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that muscular fatigue causes a distinct decrease in MPF at each turn.

In the current study, we measured SEMG signals, KJAs, and ECG during demonstration skiing of parallel turns, and we compared the muscle activities of intermediate and experienced skiers. Moreover, we studied the influence of muscle fatigue on performance during parallel skiing in terms of muscle control (which depends on skill level). To observe the influence of muscle fatigue, we also measured and analyzed SEMG signals during tube squats.

II. METHODOLOGY

A. Experimental Protocol and Measurement

A wearable measurement system was used to acquire SEMGs and KJAs during skiing. The measurement system, weighting 1.5 kg, is composed of 8/16 channels wireless unit (Myomonitor IV, Delsys) and sub-notebook PC (Let's note, Panasonic). Measured data were acquired by the attachment software (EMGworks 4.0, Delsys) with the sampling frequency at 2048 Hz. In addition, we developed a suitable GUI by using MATLAB (MathWorks) for verifying the measured data in each trial on-site.

A trial was composed of 20-min lift riding and around 5-min demonstration skiing for 4000 m. The ground had a maximum incline of 20° for the first half and a mean incline of 7° for the latter half. SEMG signals at the VL and biceps femoris (BF) with KJAs at both legs were measured by using active two-bar electrodes (DE2.3, Delsys) and goniometers (ShapeSensor S700, Measurand).

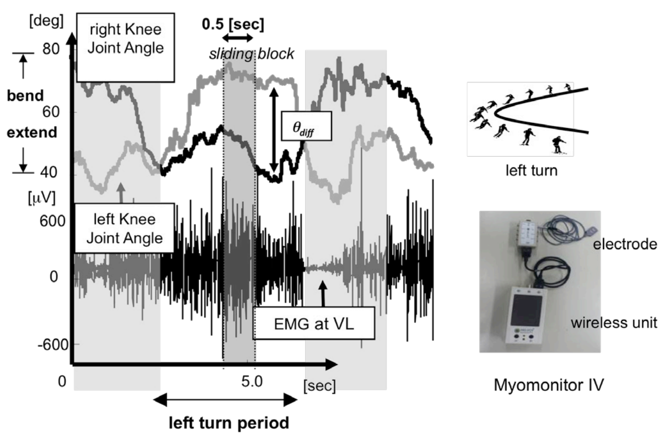

Fig. 1. KJAs and SEMG at VL for a left-turn.

B. Evaluation of Performance during Skiing

The KJA at maximum extension was set the zero degrees. For the left turn, the outside and inside legs are the right and left legs, respectively (Fig. 1). For each first half of a turn (downhill turn), the KJA trajectories of the outside and inside legs begin to part after they cross at a certain KJA, and they then cross again for the latter half of a turn (uphill turn). The right and left turns are classified according to the difference in the knee-joint angles (DKJA) between the outside and inside legs, θ_{diff} (=$|KJA_{right}$ - $KJA_{left}|$), within the turn segment. Note that according to the results of a preliminary study [9], the turn period between the KJA crossing points (Fig. 1) was determined as 1.5 to 6.6 sec. During the parallel right and left turns, KJAs are separately controlled. To control the right and left KJAs simultaneously, a certain level of skill is required. Although a carving ski allows a skier to easily control both KJAs, lack of skill regarding the parallel turn could cause a sports injury due to muscle fatigue.

C. Evaluation of Muscle Fatigue during Skiing and Squats

To evaluate muscle fatigue during skiing, we previously observed the time series of ARV and MPF for the VL muscle [9]. To estimate muscular fatigue during each turn properly, ARV and MPF from SEMG signals for each downhill turn period were estimated. ARV and MPF samples for a turn period from $\{emg(i)\}$ at the m-th turn were first estimated by a sliding-block procedure (block length and shift were 500 and 10 ms, respectively). To compare the behavior of agonist/antagonist muscle pairs in terms of strength timing, the muscle-activation pattern (ARV profile), in which the individual muscles were active at different times, is represented by a grayscale bar defined as the percentage of ARV normalized by the maximum ARV for each turn period. Note that the ARV profile was processed in advance by 20-samples moving average, and the turn duration over 10%ARV was determined.

The squat exercise is a popular pre-season ski training exercise. During the squat exercise, a similar behavior to motor control by agonist/antagonist muscle pairs is expected. During a squat exercise with a tube, the subjects who participated in the parallel ski turns were asked to try to control the knee-joint extension and flexion every 4 s for up to 100 contractions of the knee. Depending on the skill level, each subject showed a different habit to compensate muscle fatigue. The habit includes multi-joints control for sustaining the posture against muscle fatigue. The ARV profile with respect to the cycle interval was thus estimated. The ARV profiles with ensemble statistics are evaluated for several tens of consecutive contractions in a trial. Finally, basic statistics of ARV and MPF samples for each phase (early, middle, and late phase) give the behavior of ARV and MPF within a trial.

III. RESULTS

Nine healthy male subjects (27.1±11.0 yrs), whose right leg was dominant, participated in this study. The subjects were classified into two groups depending on their experience (in terms of days) regarding skiing as follows: three experienced skiers with over 100-days experience (Group G1); six intermediate skiers with over 30 to 100 days (Group G2). 3651 skiing turns were analyzed in 30 trials. The JMP statistical package (Version 7, SAS Institute Inc.) for paired t-test and ANOVA was used to analyze the results. The significant-difference level was set at $p < 0.05$.

A. Average Turn Duration in a Trial

The experienced skiers (Group G1) have the skill to control muscle activity for a sharp turn (around 2-s turn duration) and a high tolerance of muscle fatigue. As a result, in the Group G1, the turn duration was shorter (with smaller variance and almost constant θ_{diff}) than that in the case of the intermediate skiers (Group G2).

B. Change in Muscle Activation Pattern due to Fatigue

A parallel ski turn consists of a short duration and highly intensive movement. In case of group G1, a high intensity in the ARV profile of the inside leg clearly appeared for the downhill part and that of the outside leg appeared for the uphill part of a turn. This result shows a regular muscle-activation pattern and clear switching between downhill and uphill during a turn regardless of the number of turns (Fig. 2). That is, for the left turn, the left VL and BF muscles were strongly activated for the downhill part, whereas the right VL and BF muscles were strongly active for the uphill part. Group G2, however, showed neither a regular muscle-activation pattern nor clear switching. A difference in the ARV profiles of groups G1 and G2 appeared at the right BF. Actually, the experienced skiers generally showed high muscle strength as well as the appropriate skill for short-time turning [10]. The ARV profile of the BF fluctuated more than that of the VL of group G2 (Fig. 2). Moreover, MPF decreases for the first several turns and then fluctuates slightly with respect to the number of turns performed.

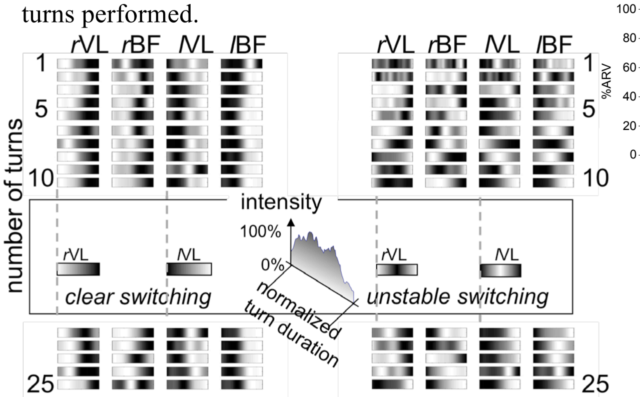

Fig. 2. Muscle activation patterns (ARV profiles) at every left turns for a typical sample from each group. *r*VL & *l*VL: right & left VL; *r*BF & *l*BF: right & left BF.

To prevent muscle fatigue, skiers change their posture, leading to low performance. Group G2 showed unstable muscle activation depending on geographical inclinations and muscle fatigue. When the intermediate skiers used the parallel turn, ARV and the KJA decreased both within a trial and among trials after repeated turns. Since the decrease in the KJA means an upright posture, it might be a sign of muscle fatigue. To sustain the posture during muscle fatigue, the group G2 skiers co-contract agonist and antagonist muscles around the knee. This was clearly shown by the ARV profile of VL and BF muscles (Fig. 2). According to the ARV and MPF samples for each turn, ARV of three of experienced skiers increased, while MPF decreased with respect to the number of turns within a trial. This result presents a clear behavior of muscle fatigue. Moreover, θ_{diff} and turn duration remained almost constant within a trial. Two of the experienced skiers showed similar behavior in ARV and MPF as a function of number of turns, while the others did not show such behavior.

C. Expected Performance during Squat Exercise

Figure 3 shows ARV profiles for each phase and MPF behaviors of the agonist/antagonist muscle pair (VL and BF) in a trial of squat exercise. High intensity of muscle activity occurred for the movement switching phase with KJA around 0.5 of a stroke cycle (KJA between 90 to 100° was corresponds to 0.5).

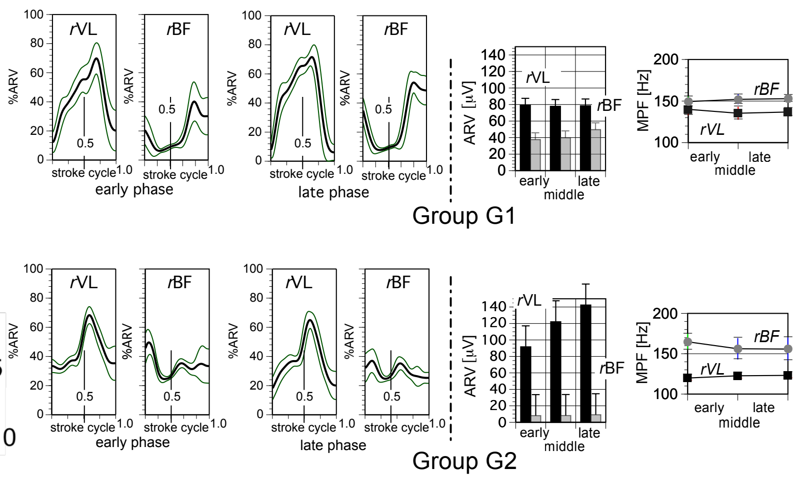

Fig. 3. ARV profiles with ensemble statistics (left) and ARV and MPF behaviors (right) for each phase during squats. KJA varied from 0 to around 100°

Group G1 showed steady muscle activation in a trial, namely, reciprocal contraction of the VL and BF in the ARV profiles as well as progressive increase in ARV of the BF and decrease in MPF of the VL. On the other hand, group G2 showed muscle fatigue, namely, co-contraction of the VL and BF in the ARV profiles, significant increase in ARV of the VL, and small decrease in MPF along with quite small activation in ARV of the BF. Note that SEMG signals at the tibialis anterior (TA) and the gastrocnemius (GAS) muscles were also measured during the squat.

IV. Discussion

Skill is related to whether peripheral muscle fatigue affects performance or not. Advanced skiers show a more regular skiing profile, that is, a muscular-activity pattern with shorter durations of activity and a higher force output

[11]. There are appropriate postures (depending on motor control) to prevent the development of muscle fatigue. Substantial muscle strength is required to completely perform the skill for controlling appropriate postures. Otherwise, the force at the knee should be distributed on agonist and antagonist muscles, leading to posture change during skiing. Hintermeister *et al.* [6] used the RMS of SEMG signals and showed the difference in average RMS for the dominant muscles for each skiing style (wedge-, parallel-, and giant-slalom). Their results showed that the rectus femoris (RF) is the most active muscle during parallel turns, the turn duration was shortest for the parallel turn and advanced skiers should concentrate on dynamic exercises of shorter duration. Specific recommendations for exercises that stabilize the knee through co-contraction of the quadriceps were made in relation to different skiing styles. Changes in muscle functional activity could be estimated from the ARV profiles for consecutive turns.

To further investigate skill level and contraction type, three muscle synergies [12] were estimated from four ARV profiles (Figs. 2 and 3). Although the number of subjects was statistically not enough, the weight coefficients of each muscle-synergy vector seemed to be related to the strong activation of the VL of the inside leg as well as the level of turning skill. This was more explicit during the squat exercise. That is, in the case of the skilled group, the weight coefficients of the VL and TA did not exist beyond the third muscle synergy, whereas in the case of unskilled group, the weight coefficients of the VL and TA still exist in the third muscle synergy. The differences in ARV profiles can reveal valuable information concerning skill. This capability would be useful in evidence-based coaching and muscle-fatigue control.

Muscle fatigue is further related to muscle-contraction types: concentric or eccentric contractions. Nilsson *et al.* [8] showed a similar eccentric–concentric muscle-activation pattern to that of telemark skiing and concluded that strength-training exercises such as barbell squats showed similar muscle action and EMG activity in the VL muscles. Even though the profile of movement was similar with each exercise, the strategy for preventing muscle fatigue in relation to performance depends on individual physical features such as skill. Motor control should thus be analyzed with SEMG signals and goniometors in terms of skill level, alternation of agonist/antagonist muscle pairs between the inside and outside legs during a parallel ski turn and regular knee flexion/extension contraction in a squat. Actually, the muscle-activation patterns of agonist/antagonist muscle pairs and θ_{diff} were different in the case of skiing and squat exercises (Fig. 3). These changes in posture or motor control probably occur to compensate fatiguing muscles in accordance with skill level.

In addition, Ebenbichler *et al*. [13] reported the changes in SEMG indices (RMS and median frequency) during isometric fatiguing knee extensions are dependent on the target force at the bi-articular muscle (RF) but not at the mono-articular muscle (VL). According to a recent review [14] presenting ARV profiles during dynamic pedaling, the mono-articular muscle produces force and the bi-articular muscle transfers energy between joints. Fatigue of the VL increases BF activation (which acts as an antagonist during knee extension). Accordingly, ARV profiles in Figs. 2 and 3 could be related to the skill level.

V. Conclusion

To present performance-related evidence in relation to the skill level and muscle fatigue, kinetic indices and muscle-activity profiles should be estimated in terms of the appropriate time scales such as consecutive turns in a trial and repetitive trials in a day. An ARV profile is superior to the ensemble mean of ARV for consecutive turns for recognizing contraction types, whereas the time-varying behaviors of ensemble indices are preferable for monitoring progressive muscle fatigue during a trial. Given this result, mono- and bi-articular muscles of agonist/antagonist muscle pairs of both legs should be investigated in a future study.

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