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Case report

Muscle Activity and Morphology in Slalom Skiing by a Single-Leg Amputee Ski Racer: A Case Study of a Paralympic Athlete

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Abstract

The aim of this study was to clarify the characteristics of skiing by a single-leg amputee ski racer from the viewpoints of muscle activity, morphology, and the relationship between both elements through comparisons with those of a non-disabled ski racer. One elite athlete, classified as LW2 (left thigh amputation), and one non-disabled athlete, as a control, participated in this study. The cross-sectional area of thigh muscles was measured through magnetic resonance imaging. Additionally, muscle activities and joint and segment kinematics during slalom skiing were measured using electromyography and inertial measurement units, respectively. The muscle activities and joint kinematics of the amputee racer in the turn in which he performed with the inside edge of the ski were similar to those of the outside leg of the non-disabled racer over a turn. In contrast, at the turn in which the amputee racer performed with the outside edge (more difficult side), the amputee racer largely activated the biceps femoris (BF) in the first half of the turn compared to the non-disabled racer. The reason could be to control the angular momentum of the trunk during the forward tilting motion. This is because a greater activity of the BF was observed during the period in which the forward tilt of the trunk was increased, and the mean activity of the BF was the greatest during the first half of the right turn in which the range of the motion of the forward tilt was the greatest. In terms of muscle morphology of the amputee racer, a significant hypertrophy of the BF and vastus lateralis was observed compared to the non-disabled racers. The well-developed BF was considered to be related to the large activity during the turn performed with the outside edge of the ski.

Key words: Paralympic alpine skiing, electromyography, muscle cross-sectional area, magnetic resonance imaging, inertial measurement unit.

Introduction

In all Paralympic sports, including Paralympic alpine skiing, "classification" is undertaken to "group Athletes into Sport Classes which aim to ensure that the impact of Impairment is minimised and sporting excellence determines which Athlete of team is ultimately victorious" (World Para Alpine Skiing, 2017). The classification is specific to sports, and there are three categories of para-alpine skiing: standing, visually impaired, and sitting. The standing class includes sport classes of LW1-LW9 which are determined based on the impairments of athletes. In the case of leg amputation, performance is significantly affected by the presence of knee function. If knee function remains, numerous athletes ski with both legs using prosthetic legs, whereas thigh amputees often ski with one leg. They are usually allocated to different classes. Although it is easy to imagine that the load on one leg is greater when skiing with a single leg than when skiing with both legs, no studies have examined how single-leg amputee ski racers still manage to ski and compete in races. Additionally, considering the unstable conditions during skiing, it is assumed that single-leg amputee alpine ski racers adopt strategies to maintain their balance than non-disabled ski racers and have developed muscles that are involved in their skiing strategies. However, no studies have examined how amputee ski racers control their posture and ski.

Electromyography (EMG) during skiing provides useful information regarding how ski racers control muscles, that is, their posture and ski. Some studies have been conducted on muscle activity during skiing in non-disabled alpine ski racers (Berg et al., 1995; Hintermeister et al., 1995). Nonetheless, to the best of our knowledge, no studies have focused on muscle activity during skiing by single-leg amputee ski racers. Therefore, we used EMG to clarify the characteristics of skiing using a single-leg amputee ski racer as a first study.

In addition, we focused on the relationship between muscle activity and morphology. We presumed that thigh muscle morphology develops according to muscle activity during skiing. In other words, we can speculate the characteristics of skiing by a single-leg amputee ski racer from the viewpoint of muscle morphology.

Therefore, the aim of this study was to clarify the characteristics of skiing by a single-leg amputee ski racer from the viewpoints of muscle activity, morphology, and the relationship between both elements through comparisons with those of a non-disabled ski racer.

Methods

One single-leg amputee ski racer of the Japanese National Paralympic Alpine Ski Team (age, 31 years; height, 1.64 m; body mass, 65.6 kg) and one non-disabled ski racer (age, 25 years; height, 1.74 m; body mass, 79.3 kg; Slalom FIS point, 93) participated in this study. The single-leg amputee ski racer is a male standing-class athlete, who skis with one ski and two outriggers and is classified as LW2. He has experience in four Paralympic Games (Torino 2006, Vancouver 2010, Sochi 2014, and Pyeongchang 2018). Both the amputee and non-disabled athletes participated in both laboratory and on-slope field measurements.

The athletes provided written informed consent to participate in this study; the study was approved by the ethics committee of the Japan Institute of Sports Sciences

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Laboratory measurements

A 3-T superconducting magnetic resonance imaging (MRI) device (Magnetom Verio, Siemens Healthineers, Erlangen, Germany) was used to obtain MR images to measure the cross-sectional area (CSA) of the thigh muscles. The athletes were placed in the supine position. First, localisation images were obtained from three anatomic planes (sagittal, coronal, and transverse). Next, transverse fast spin-echo images (repetition time: 500 ms; echo time: 8.2 ms; matrix: 256 × 256; field of view: 240 mm; thickness: 10 mm) were obtained halfway between the trochanter major and the tuberculum intercondylaris using a body coil. The CSAs of the thigh muscles of the Japanese National Alpine Ski Team members in 2005 (age: 25 ± 3 years; height: 1.76 ± 0.03 m; body mass: 78.9 ± 5.1 kg; mean ± standard deviation) are also shown for reference, which were also measured using this protocol.

On-slope field measurements

Field measurements of the amputee and non-disabled athletes were performed in February and March, respectively, at the Kazawa ski area, Nagano Prefecture, Japan, as the amputee athlete was in the competitive season.

To simulate racing conditions, the amputee athlete performed two consecutive slalom (SL) runs separated by 15 min in a course (20 ° average slope angle, 121 m vertical drop, and 349 m course length). The runs lasted approximately 34 s. Forty-one SL gates were set by the team's head coach on the slope. Snow conditions were hard. The non-disabled athlete performed three consecutive SL runs on the same slope. Because of a fall, three measurements were taken. A course with 12 open gates with an equal direct distance (interval) (9.0 m) and horizontal distance (3.0 m) between successive turning poles was set. To make the course similar, those distances were determined to approximately coincide with the tightest interval between successive open gates of the course used for the measurement of the amputee athlete (interval: 9.1 m, horizontal distance: 2.7 m).

Figure 1. The locations of the inertial measurement units on the athlete's body segments (pelvis, right thigh, and right shank).

To measure the hip and knee joint angles, three inertial measurement units (IMUs) were placed on the athlete's body segments (pelvis, right thigh, and right shank) (Figure 1). These IMUs were affixed along the segment coordinate systems defined according to Wu et al. (2002). The IMU used in the current study was custom-made (Yoshioka et al., 2018). It comprised gyroscopes and an accelerometer. Signals from the IMU were sampled at 1 kHz. Initial back-forth and right-left tilts of the body segments in a trial were obtained from photographs taken from the side and back of the subject. The initial back-forth and right-left tilts of the IMU were determined from the direction of the gravitational acceleration measured by the accelerometer. The relative orientation between a segment and the IMU attached to the segment, which was constant during the experiment, was calculated using the initial orientations of the segment and the IMU. The orientation of an IMU during skiing was obtained by integrating the angular velocities measured by the gyroscopes. Then, the orientation of the segment to which an IMU was affixed, was calculated using the orientation of the IMU and the relative orientation between the segment and the IMU (Yoshioka et al., 2018).

During skiing, EMG was monitored via telemetry using a four-channel transmitter (Mini Wave Waterproof, Cometa Systems; Bareggio, Italy). EMG signals were sampled at 2000 Hz and recorded on a logger. For placement of the surface electrodes, the skin was cleaned with alcohol. Bipolar (~2 cm separation) surface electrodes (Ag-Ag/Cl) were placed over the following four thigh muscle groups on the right side of the body: vastus medialis (VM), vastus lateralis (VL), rectus femoris (RF), and long head of biceps femoris (BF). Proper electrode placement was confirmed using manual muscle testing.

Isometric maximum voluntary contractions (MVC) utilising manual loads were performed before or after the gate runs and provided a relative reference for the EMG amplitude during skiing. MVCs for the quadriceps (VM, VL, and RF) were measured by the following two procedures with the subject sitting on the edge of the chair: (1) the subject flexed his knee at 90° and maximally contracted the quadriceps while a manual load was applied in the direction of knee flexion; and (2) the subject fully extended his knee and maximally contracted the quadriceps (tried to raise his straight leg) while a manual load was applied in the direction of hip extension. The MVC for the BF was measured in the prone position with the subject's knee flexed at 45 °, whereas the BF was maximally contracted while a manual load was applied in the direction of knee extension. Each series comprised two MVCs with a duration of approximately 3 s and a relaxation period of similar duration between the contractions.

EMG recordings and IMU data were genlocked, and synchronisation was accomplished using a manually triggered synchronisation switch.

Data analysis

The obtained transverse image was transferred to a computer using customised software (ISIS, Hitachi; Tokyo, Japan), and the CSAs of the thigh muscles (VM, VL, RF, and

BF) were calculated. Both long and short heads of BF were included in the calculation of the CSA of the BF.

Each run of the amputee athlete was divided into 17 cycles; each cycle consisted of one left turn and one right turn (Figure 2). For each cycle, three maximal and two minimal flexion angles of the knee joint and hip joints were identified. A left turn was defined as the phase from the first to the second maximum of the knee joint, and a right turn was defined as the phase from the second to third maximum of the knee joint. A concentric (CON) muscle action was defined as the phase from the maximum to the minimum knee flexion angle. An eccentric (ECC) muscle action was defined as the phase from the minimum to the maximum knee flexion angle (Figure 3).

For the non-disabled athlete, only the fourth cycle of the first run, in which the EMG of the four muscles of the right leg could be completely measured, was used for subsequent analysis, because, in other cycles, sensor communication failures occurred for one or two muscles, or data loss occurred due to collisions between the EMG sensor and gate pole. The phases were determined to correspond with those of the amputee athlete, and the mean rectified EMG was calculated according to the phases.

To evaluate the difference in turn duration between the left and right turns, five left and right turns in the open gate sandwiched between open gates before and after the gate itself were selected. The turn duration of the non-disabled athlete was determined by defining the turn-switching time as the time when the angles of the right and left knees were equal.

The hip and knee joint flexion angles were calculated from the orientations of the pelvis, right thigh, and right shank segments according to the definitions recommended by the International Society of Biomechanics (Grood and Suntay, 1983; Wu et al., 2002). The pelvis tilts were expressed using Euler angles between the segment coordinate systems of the pelvis and the global coordinate systems. The forward tilt was defined as the angle of the second rotation of the Euler angles consisting of three sequential rotations (the first: vertical axis of the global coordinates; third: the posterior-anterior axis of the pelvis coordinates; and second: the axis perpendicular to both the first and third axes). A forward tilt of 0 degrees indicated a posture of the pelvis similar to that when a human stands upright on a horizontal plane. Positive and negative values of the angle indicate forward and backward tilt of the pelvis, respectively.

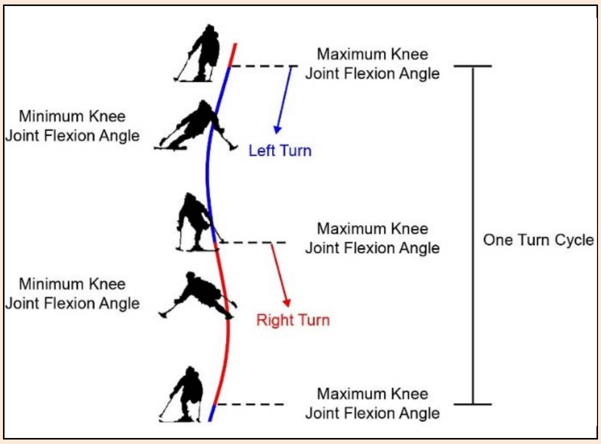

Figure 2. Definition of a turn cycle.

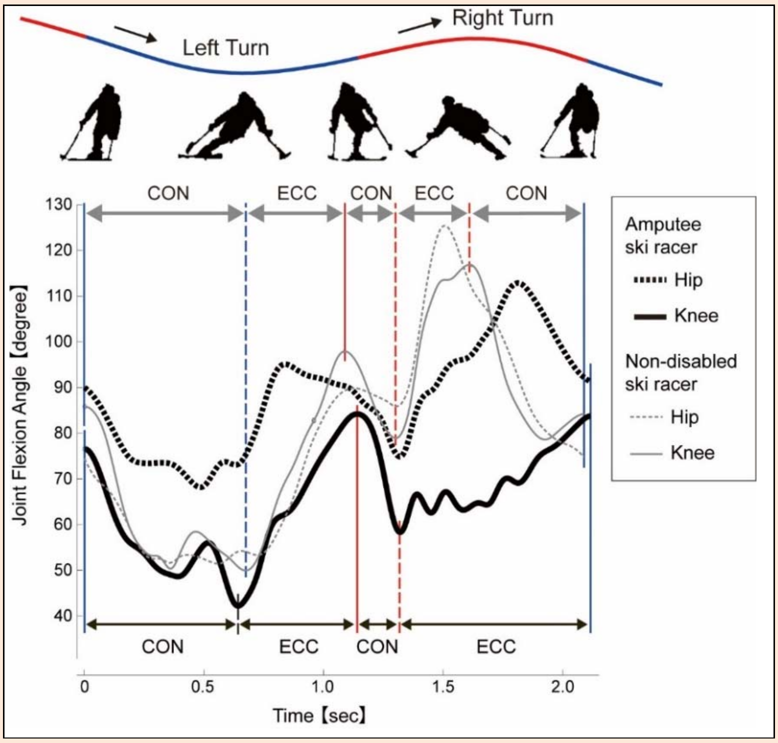

Figure 3. Temporal pattern of the knee and hip joint flexion angle during one typical turn cycle. CON: concentric phase, and ECC: eccentric phase. Note that the results of the right turn of the non-disabled athlete show the behaviour of not the outside leg but the inside one. It was not used in the comparison with the amputee athlete but has been provided to show the turn characteristic of the non-disabled athlete for reference.

The raw EMG data signals (both skiing and MVC trials) were high-pass filtered at a cut-off frequency of 20 Hz (Jacobs and van Ingen Schenau, 1992). The EMG signals were then full-wave rectified. The rectified EMG signals for the MVC trials were averaged (average rectified values: ARV) at 1 s intervals. The highest value of the 1-s ARV among MVC trials for each muscle was used to normalise the EMG signals during the skiing trials. EMG signals were expressed as a percentage of MVC. Then, the signals were low-pass filtered at a cut-off frequency of 10 Hz to understand the temporal patterns. The muscle activities during CON, ECC, and total (CON and ECC) were assessed by computing the mean value of the smoothed signals at the corresponding phases. EMG parameters were analysed with software (MATLAB R2019b, MathWorks; Natick, MA) that incorporated the phase boundaries identified from the joint angle analysis. Several instances of missing EMG data were observed owing to signal problems.

Statistical analysis

The difference in the left and right turn durations were tested for significance using Student's unpaired t-test at the 5% significance level. The effect size of Cohen's d was calculated and evaluated according to the following criteria: trivial (< 0.20), small (0.20 - 0.59), moderate (0.60-1.19), large (1.20 - 1.99), and very large (2.00 - 3.99) (Hopkins, 2000).

Results

The temporal patterns of the EMG and joint angle during the left turn of the amputee and the non-disabled athletes were similar (Figure 3, Figure 4 and Figure 5).

The mean and standard deviation of the left and right turn durations of the amputee athlete were 1.09 ± 0.13 s and 0.83 ± 0.14 s, respectively. The duration of the right turns was shorter than that of the left turn ($t = 3.11$, effect size = 1.97, $p = 0.01$). Those of the left and right turn of the non-disabled athlete were 1.05 ± 0.06 s and 0.99 ± 0.09 s, respectively ($t = 1.23$, effect size = 0.78, $p = 0.25$).

Figure 6 shows images of the right thigh muscles of the amputee and non-disabled athletes. Both the non-disabled athlete in this study and the national team members had similar CSAs. The CSAs of the BF and VL of the amputee athlete were clearly different from those of the non-disabled athletes (the non-disabled athlete in this study and the national team members) (Table 1).

Representative EMG recordings and the mean rectified EMG are shown in Figure 5 and Figure 6, respectively. The activity of the VM was consistently higher than those of the other muscles. A large BF activity was observed in the first half of the right turn of the amputee athlete.

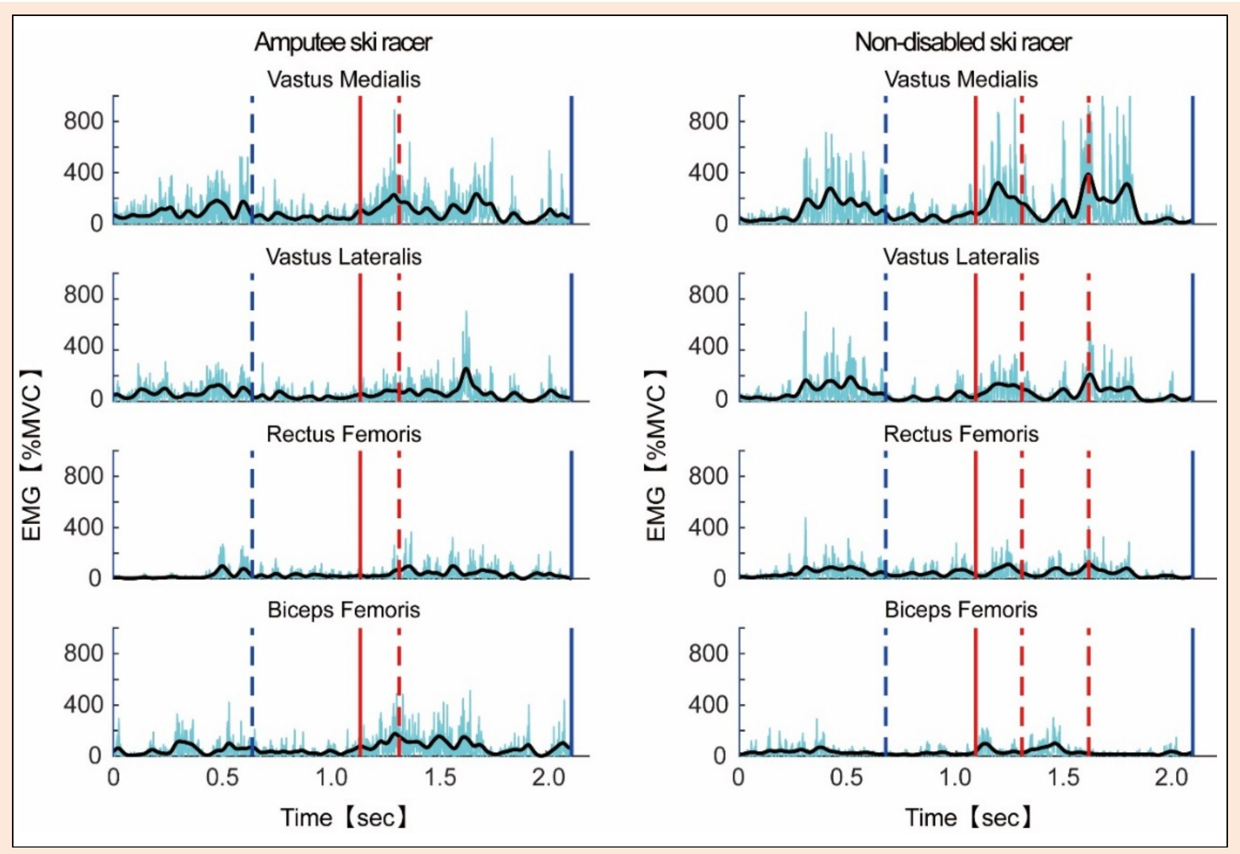

Figure 4. Temporal pattern of EMG of vastus medialis (VM), vastus lateralis (VL), rectus femoris (RF), and long head of biceps femoris (BF) at one typical turn cycle. The light blue lines show the rectified EMG signal, and black lines show the smoothed rectified EMG signal.

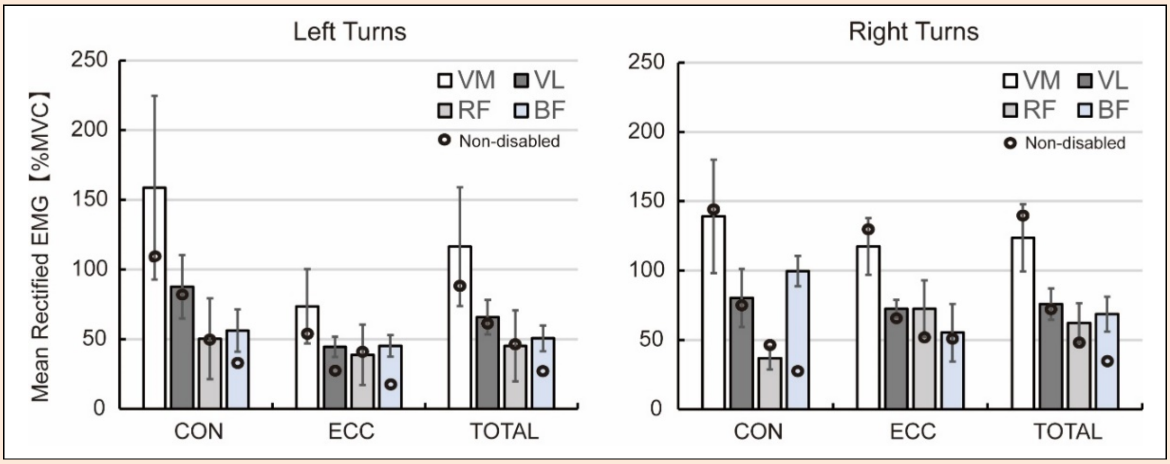

Figure 5. Comparison of the means of the smoothed rectified EMG signals of the amputee athlete: vastus medialis (VM), vastus lateralis (VL), rectus femoris (RF), and long head of biceps femoris (BF) at concentric (CON), eccentric (ECC), and both CON and ECC phases (TOTAL). The circles superimposed on the bar graph indicate the value of the non-disabled athlete in one typical turn cycle shown in Figure 4.

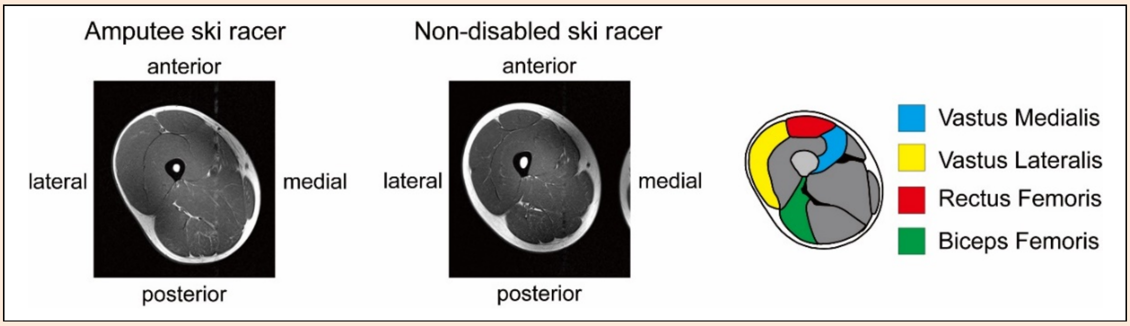

Figure 6. The left two figures show the MR imaging scans at 1/2 femur height of the single-leg amputee and the non-disabled ski racers. The right figure shows the general classification of the targeted muscles (VM: vastus medialis, VL: vastus lateralis, RF: rectus femoris, and BF: long and short heads of biceps femoris).

Table 1. Cross-sectional areas of thigh muscles (vastus medialis, vastus lateralis, rectus femoris, and biceps femoris) at 1/2 femur height of the amputee and the non-disabled ski racers of this study and the alpine ski racers of the Japan National Alpine Ski Team.

	Cross-sectional areas of the thigh muscles 【cm^2】			
	Amputee ski racer (n=1)	Non-disabled ski racer (n=1)	Japan National Alpine Ski Team (n=6) mean ± SD	95 % CI
Vastus Medialis	22.8	23.2	19.0 ± 2.2	(16.6, 21.3)
Vastus Lateralis	41.2	32.5	37.1 ± 2.3	(34.7, 39.6)
Rectus Femoris	13.4	10.4	12.3 ± 2.0	(10.2, 14.3)
Biceps Femoris	25.3	15.1	16.7 ± 1.9	(14.7, 18.6)

Discussion

The leg motion of the amputee athlete during the left turn was similar to that of the outside leg of the non-disabled athlete during both the left and right turns, as estimated from muscle activity and joint motion. This is presumably because the amputee athlete performed the left turn mainly with the inside edge of the ski, similar to the non-disabled athlete. These results indicate that knowledge regarding the turns of non-disabled racers can be applied to the inside edge turns of single-leg amputees. However, the baseline of the hip joint angle was different between the amputee and non-disabled athletes. It is unclear whether these differences are due to differences in the position of the centre of mass, for example, or those in the load on the inner ski due to the absence of the left leg.

VM was activated more than VL, regardless of the type of athlete (amputee/non-disabled), phase (CON/ECC), and turn (left/right). Assuming that the loads on VM and VL are similar, one of the reasons is that VM has a smaller CSA than VL (Table 1). It is currently unknown whether there is a functional difference between VM and VL.

The right turns of the amputee athlete, which were performed with the outside edge of the ski, and which are more difficult from the viewpoint of balance control, took less time than the left ones performed with the inside edge of the ski (effect size = 1.97, large effect, p = 0.01). Although the effect of slope condition may be a factor, the effect size of the amputee athlete was larger than that of the non-disabled athlete (effect size = 0.78, moderate, p = 0.25). Therefore, the asymmetry of turn duration was considered to be related to thigh amputation. It is unclear what caused the difference in the right and left turn durations. This is an interesting topic for future research. Additionally, this result indicates that the direction was rapidly changed during the right turn, that is, a large external force was generated. This large external force may be one of the factors that caused the larger activities of the vastus muscles (VL and VM) in the ECC of the right turn than those in the CON and ECC of left turn (Figure 5).

The most prominent difference in the muscle activities that discriminated the amputee athlete from the non-disabled athlete was the magnitude of BF activity in the first half of the right turn of the amputee athlete. This seemed to be related to the forward tilt of the trunk. Figure 7 shows the forward tilt of the trunk (pelvis segment) and BF activity at one typical turn cycle. As the trunk began to tilt forward, the BF activity synchronously increased, and with the cessation of the forward tilting motion, it also decreased. Furthermore, the mean BF activity was greatest during the first half of the right turn of the amputee athlete, in which the range of the forward tilt motion was the greatest. These results and the anatomy of BF indicate that the role of the BF was to control the large angular momentum of the trunk that occurs during the period in which the forward tilt of the trunk was increased.

The large activity of the BF may be related to the fact that the CSA of the BF was considerably larger than that of the non-disabled racers (Table 1). Nuell et al. (2020) showed that sprint-based training seemed to lead to selective hypertrophy of the muscles associated with sprinting, that is, there is a possibility that the execution of a motion itself causes hypertrophy of the muscles associated with the motion. Additionally, numerous studies have shown that muscle strength training causes an increase in not only CSA but also EMG of the trained muscle (e.g. Häkkinen et al., 1998). These findings support the existence of an association between the magnitude of BF activity and hypertrophy. However, the causality of these relationships remains unknown. The VL of the amputee athlete was also hypertrophied compared to those of non-disabled athletes, including the national-level athletes. However, unlike BF, no differences in activity during the turn were observed between athletes. Because the difference in the CSA of VL was small compared to that of BF, it is possible that no difference in activity was observed. Further studies are needed to determine whether hypertrophy is associated with skiing.

Although the contribution to balance has not been quantitatively examined, the outriggers are considered to have played a role in maintaining balance by amputee skiers. The effect of outriggers on muscle activities from the viewpoint of balance was not examined in this study. Therefore, its effect is an issue that should be addressed in the future.

These results cannot be generalised because only one athlete was studied, which is a limitation of this study. In the Japanese Paralympic Alpine Ski Team's standing category, there is only one athlete with an amputated leg. If a ski racer's competition level is set to a certain level, only one person in this study is eligible. In the future, it will be necessary to perform the same measurement and verification for ski racers from other countries. However, even considering this limitation, the value of this study holds because our findings have not been shown in studies focusing on non-disabled ski racers and provide facts that will lead to a further understanding of general amputee skiers as well as amputee ski racers.

The results of the present study provide valuable information regarding an elite single-leg amputee ski racer. He activated BF more actively to control the forward tilt of his trunk, especially in the first half of the turn performed with the outside edge of the ski. To enhance the performance of athletes who will begin skiing with one ski or non-elite amputee ski racers, the data obtained from this elite athlete will be important reference. Additionally, this study showed that BF and VL hypertrophy in a single-leg amputee athlete, even when compared to elite non-disabled Olympic athletes. Although it is possible that long-term experiences in single-leg skiing have caused hypertrophy in the thigh muscles, training session to strengthen these muscles should be beneficial to enhance performance in skiing.

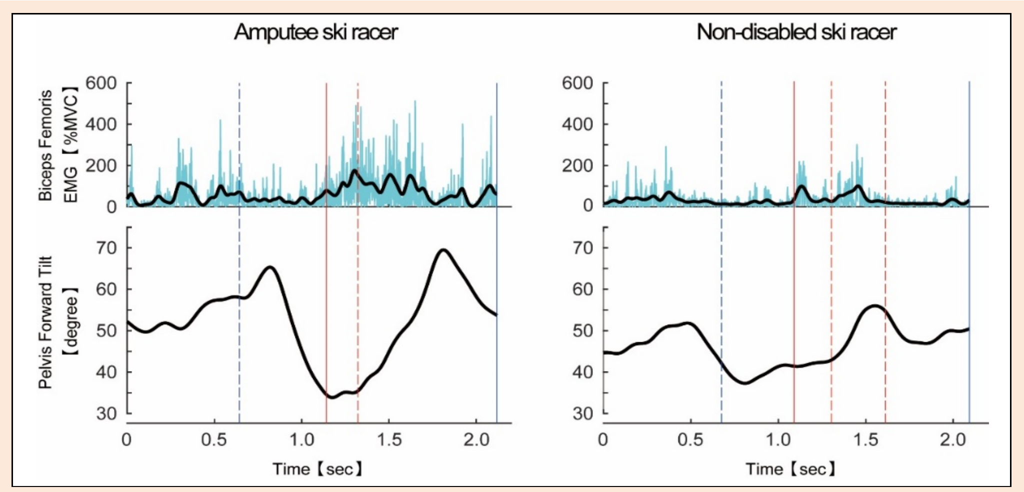

Figure 7. Temporal pattern of the pelvis forward tilt and EMG of the long head of biceps femoris at one typical turn cycle. A forward tilt of 0 degrees denotes a posture similar to that when standing upright on a horizontal plane.

Furthermore, considering the motion, for BF strength training, single-leg deadlift (Diamant et al., 2021) may be suitable in terms of its similarity to the skiing motion itself as it uses a forward tilt of the trunk to load the hamstrings. If the emphasis is on placing a greater load on the hamstrings rather than similarity in movement style, Nordic hamstrings (Mjølsnes et al., 2004) may be a candidate.

Conclusion

The present study highlighted the characteristics of skiing by an elite single-leg amputee ski racer and his well-developed muscle morphology through comparisons with those of non-disabled racers. The muscle activities and joint kinematics of the amputee athlete in the turn in which he performed with an inside edge of the ski were similar to those of the outside leg of the non-disabled athlete. In contrast, during the turn in which the amputee athlete performed with the outside edge, the amputee athlete largely activated the BF in the first half of the turn compared to the non-disabled athlete.

The reason was considered to control the angular momentum of the trunk occurred during the period in which the forward tilt of the trunk was increased. In terms of the muscle morphology of the amputee athlete, the well-developed BF was considered to be related to the large activity during the turn performed with the outside edge of the ski.

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Key points

- An elite single-leg amputee ski racer, classified as LW2 (left thigh amputation), has a well-developed thigh muscle (vastus lateralis and biceps femoris) morphology compared to non-disabled alpine ski racers, including elite racers.
- To accomplish turns in which the amputee racer performed with the outside edge (more difficult side in terms of balance control), the amputee racer largely activated the biceps femoris in the first half of the turns. The reason could be to control the angular momentum of the trunk that occurred during the period in which the forward tilt of the trunk was increased.
- The well-developed biceps femoris of the amputee racer was considered to be related to the large activity during the turn performed with the outside edge of the ski.

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Research interests

Sports Biomechanics

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