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**Case report**

# The Influence of Trunk Impairment Level on the Kinematic Characteristics of Alpine Sit-Skiing: A Case Study of Paralympic Medalists

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## Abstract
This study aimed to examine the relationship between the trunk impairment level and the trunk kinematic characteristics during alpine sit-skiing from a classification perspective. Three Paralympic medalists in sitting classes (LW10-2, LW11, and LW12-2) participated in the present study. To simulate the racing conditions, giant slalom gates were set. To measure the kinematics of the skier and sit-ski during skiing, a motion capture method with inertial measurement units was used. The muscle activities of the trunk muscles were evaluated using electromyography. Chest lateral flexion, chest flexion, and hip flexion/extension angle during sit-skiing were reduced due to impairment. Additionally, the insufficient lateral flexion (angulation) caused a decrease in edging angle, and that the insufficient chest and hip flexion/extension caused a lower loading in the latter half of the turn through smaller vertical movement. Since edging angle and loading are key factors in ski control, the three joint motions could be measures of sport-specific activity limitation in sit-skiing classification. Between the LW10-2 and LW11 skiers, no distinct differences in trunk kinematics were found. Assuming the scaling factor of race time as a measure of skiing performance, one possible reason is that the difference in skiing performance the LW10-2 and LW11 skiers is considerably smaller relative to differences between the LW11 and LW12-2 skiers. There were no distinct differences among classes in the results of muscle activity, and therefore, this information appears to play a minimal role for classification.

**Key words:** Paralympic alpine skiing, classification, monoski, giant slalom, inertial measurement unit.

## Introduction

In recent years, the number of studies on Paralympic sports, such as that by Keogh, has been increasing (Keogh, 2011; Morriën et al., 2017). In particular, research related to classification has increased significantly (Mann et al., 2021). This is primarily because the International Paralympic Committee (IPC, www.paralympic.org) requires the development of a sport-specific and evidence-based classification system through scientific research in its Athlete Classification Code (Article 10.2.1). However, the progress of classification research varies with different sports. Unfortunately, research on the classification of alpine sit-skiing (e.g., Goll et al., 2018) is limited relative to other sports such as athletics (Connick et al., 2018) and swimming (Hogarth et al., 2018). Researchers engaged in alpine sit-skiing must provide scientific knowledge that contributes to the classification.

Studies on alpine sit-skiing have been conducted in physiology (Goll et al., 2012; 2015b), biomechanics (Goll et al., 2015a; 2018; Petrone et al., 2020), sit-ski development (i.e., the composite of bucket seats, frames, and suspension units consisting of dampers and springs) (Cavacece et al., 2005; Langelier et al., 2013), and scaling factor of race time (Percy and Warner, 2008). Physiological studies by Goll et al. (2015b) have shown that the metabolic demands of skiers during sit-skiing are low compared to the demands required when performing at their maximum capacity. This finding indicates that aerobic and anaerobic performances are not important factors directly associated with sit-skiing performances; therefore, it is imperative that future research focuses on the impairments related to biomechanical factors such as skiing technique and equipment.

Sit-skiers control their skis with their trunk (Goll et al., 2018). Therefore, trunk impairment is believed to lead to activity limitations during skiing. In the case of sit-skiers, the more severe the impairment, the more the loss of control extends to the upper region of the trunk (World Para Alpine Skiing Classification Rules and Regulations, 2017). Since the mechanism of the spine's functioning is such that the whole movement arises as a sum of small movements between the vertebrae (Schünke et al, 2014), the trunk motion is limited in proportion to the impairment level. Therefore, the range of motion of the trunk on land can be considered a candidate of the sport-specific activity limitation defined by the IPC. Identifying the relationship between the range of motion of the trunk on land and sit-skiing performance has served as a key theme in the development of objective classifications in recent years. To establish the importance of this topic, it is worthwhile to quantify the amount of movement of the trunk during sit-skiing and then to identify the primary differences in the trunk movement between sit-skiers with different levels of impairment. However, to our knowledge, no studies have examined these predictors of activity impairment among skiers. Therefore, the present study aimed to examine the relationship between the impairment level and the trunk kinematic characteristics during alpine sit-skiing from a classification point of view.

The control of edging angle via angulation is the most important mechanical principle in alpine skiing (Howe, 2001). Since angulation during sit-skiing is controlled by the lateral flexion of the trunk, its limitation is considered to have a significant effect on sit-skiing. During slalom racing by able-bodied skiers, it has been reported that the angulation angle approached 40 degrees at the hip (Supej et al., 2005). The angle is approximately the same

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as the total range of lateral flexion in the thoracic and lumbar spinal regions (Schünke et al, 2014), meaning that even those with no limitations in the trunk lateral flexion have no extra range of motion when sit-skiing. This fact suggests that if the maximum lateral flexion of the trunk during skiing is constrained according to the impairment level, the resultant maximum angulation is also constrained. Since the amount of the angulation, in combination with the inclination of the center of mass of the skier's body, determines the edging angle and affects the minimum radius of a carving turn (Komissarov, 2020), insufficient angulation is expected to be disadvantageous in competition performance. Therefore, the present study focused especially on the lateral flexion of the trunk.

The present study was conducted as a case study because the population of alpine sit-skiers was quite small and a large number of sit-skiers with the same skill and impairment level could not be evaluated. However, because all three skiers who participated in the present study were medalists at the winter Paralympic games, the knowledge obtained through the present study is considered useful for evidence-based classification.

## Methods

Three sit-skiers (two men and one woman) from the National Paralympic Alpine Ski Team (mean age, 28.3 ± 4.6 years; mean arm span, 1.73 ± 0.06 m) participated. They were classified as LW10-2, LW11, and LW12-2, respectively. Lower class numbers correspond to those in a class with more severe impairment. The impairments of the skiers in LW10-2/LW11 classes were spinal cord disorders at the T10 and T11 lesion levels, respectively. The LW12-2 skier had amputations of both lower limbs at the thigh level due to a traumatic accident. The skiers had participated in one to four winter Paralympic games (Torino 2006; Vancouver 2010; Sochi 2014; Pyeongchang 2018), where each skier won three to five medals. They provided written informed consent to participate in the present study, which was approved by the ethics committee of the institution to which the authors belong.

Field measurements were conducted at two ski areas in Japan. For each of the three skiers, the measurements were performed on a different slope and a set of gates according to their training schedules. The mean (maximum) angles and vertical drops of slopes were approximately 12°–15° (23°–28°) and 150–180 m, respectively. Snow conditions were hard. To simulate racing conditions, 18 to 26 giant slalom (GS) gates (32–53 s) were set by the team's head coach on slopes. Two skiers performed two GS runs, and the second run was used for further analysis. In the other skier, only one run was measured owing to the constraint of the training schedule, and the run was used for further analysis. To evaluate the effect of differences in skiing conditions (slope and gate setting) on the results, trunk kinematics during free-skiing (middle turn with a slalom ski) on the same slope (mean and maximum angles: 15° and 23°) among all three skiers were additionally measured as a reference. All skiers used their own equipment. All their frames were produced by Nissin (Nissin Medical Industries Co., Ltd., Aichi, Japan). The backrest heights of the bucket seats of the LW10-2, LW11, and LW12-2 skiers were approximately 45%, 45%, and 30% of the total length of the lower and upper trunk segments, respectively.

To measure the kinematics of the skier and sit-ski during skiing, the motion capture method with inertial measurement units (IMUs) was used (Yoshioka et al., 2018; Ishige et al., 2021). The skier and sit-ski were modeled with five segments (upper trunk, lower trunk, seat, four-bar, and ski-foot segments) and four joints with three degrees of freedom (chest, hip, sit-ski upper, and sit-ski lower joints; Figure 1a). The mechanical foot and ski were assumed to be one rigid body as a ski-foot segment. The mean length of upper trunk, lower trunk, seat and four-bar segments were 0.37 ± 0.10 m, 0.23 ± 0.04 m, 0.35 ± 0.03 m and 0.33 ± 0.01 m, respectively. The mean height of hip joint was when stationary at the start was 0.41 ± 0.03 m. The suspension length was calculated from the motion of a sit-ski and its connected locations to the sit-ski. The mean suspension length when stationary at the start was 0.29 ± 0.02 m. An IMU was placed on each segment (Figure 1b).

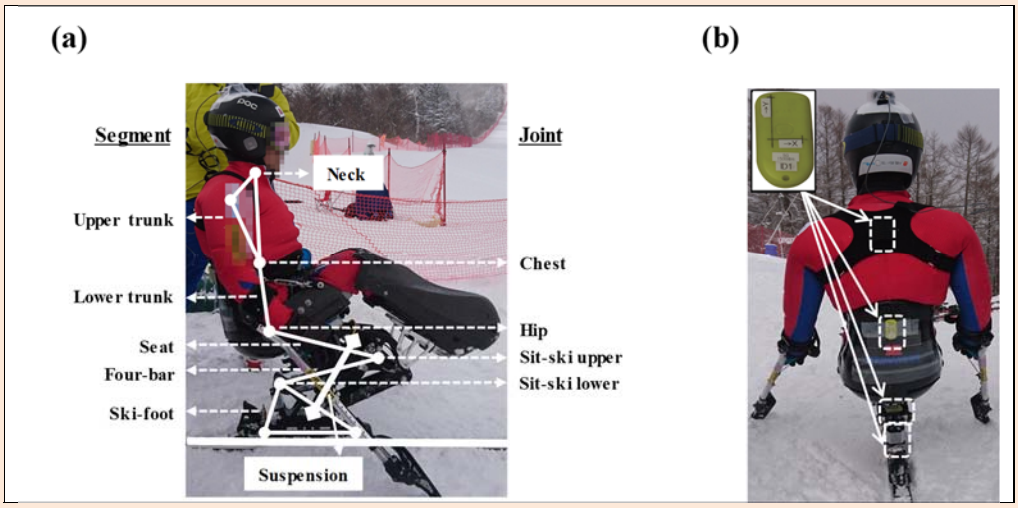


**Figure 1. (a) The model representing sit-skier, sit-ski, and ski. It was modeled by five segments and four joints connecting to those segments. (b) Locations of inertial measurement units (IMUs). An IMU is placed on each segment. No IMU on a seat segment is visible in this figure.**

The IMU consisted of three axial gyroscope and three axial accelerometer. Signals from IMUs were sampled at 1,000 Hz. Initial back-forth and right-left tilts of a body segment in a trial were obtained from photographs taken from the side and back of the skier. The initial back-forth and right-left tilts of an IMU were determined from the direction of the gravitational acceleration measured with accelerometers. The relative orientation between a segment and the IMU attached to the segment was calculated with 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 gyroscopes. Subsequently, the orientation of the segment to which an IMU was affixed was calculated with the orientation of the IMU and the relative orientation between the segment and the IMU. Kinematic data were low-pass filtered at a cut-off frequency of 10 Hz with a fourth-order Butterworth filter. The cut-off frequency was determined using a residual analysis (Winter, 2009).

The electromyography (EMG) signals of the trunk muscles were measured to reveal the muscle activity related to severity of impairment. They were sampled at 2,000 Hz and recorded on a logger (Mini Wave Waterproof, Cometa Systems; Bareggio, Italy). Bipolar (approximately 2-cm separation) surface electrodes were placed over the following five kinds of trunk muscles on both sides of the body: 1) serratus anterior (SA), 2) rectus abdominis (RA), 3) abdominal external oblique (EO), 4) erector spinae (ES), and 5) quadratus lumborum (QL). A physical therapist and/or an acupuncturist who were members of the ski team assisted in identifying the location of the muscles. One skier had atrophy or deficiency of the QL; therefore, the EMG signals of the right and left QL muscles were not measured. One skier failed to undergo measurements of the right and left RAs for technical reasons. The EMG and IMU data were synchronized with a trigger switch. Isometric maximum voluntary contractions (MVCs) utilizing manual loads were collected after the GS runs and provided a relative reference for the EMG amplitude during skiing. Two MVC trials were conducted with a duration of approximately 3 seconds with a relaxation period of similar duration between the contractions. The raw EMG data signals during 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-second intervals. The highest value of the 1-second ARV among the MVC trials for each muscle was used to normalize the EMG signals of those during the skiing trials. EMG signals were expressed as percentages of the MVC. Subsequently, the signals were low-pass filtered at a cut-off frequency of 2 Hz to show the temporal patterns.

The chest joint angle was expressed using the Euler angle. The order of rotation (flexion/extension, lateral flexion, and rotation about the long axis of the lower trunk) was determined in accordance with the recommendation of Grood and Suntay (1983). The hip-joint angle was calculated as a uniaxial joint (flexion/extension). The lateral flexion at chest joint was regarded as the measure of angulation, because the chest joint is the only joint that contributes to angulation in the case of sit-skier.

Edging angle was calculated by referring to Yoneyama et al. (2008). First, the normal vector of the slope during one turn was calculated from the orientation of the ski at the moment when the ski was most inclined to the horizontal plane during the turn (facing the "fall line"). We assumed that the slope change during one turn was negligible. Next, the angle between the normal vector of the slope and that of the ski running surface was calculated, and this angle was defined as the edging angle.

The acceleration caused by the resultant force of the external forces (the ground reaction forces through a ski and two outriggers and air resistance) was calculated by subtracting the gravitational acceleration from the acceleration data obtained from the IMU attached to the ski seat (lower trunk). This acceleration is primarily caused by the ground reaction force through a ski due to the following reasons: The air resistance under the environment of GS sit-skiing is reportedly approximately 100 N (Vinagre, 2012), and its contribution to the total external force is estimated to be 10–20%. Although the contribution of outriggers is unknown, it is estimated to be even smaller, as the main role of outriggers is not to transfer force between the snow surface and the body, but rather to maintain balance. The measured acceleration was low-pass filtered at a cut-off frequency of 2 Hz.

In the analysis, each run was divided into right and left turns. All but two turns after the start, two turns before the goal, and the turn at a delayed gate were analyzed. One run had 5 to 9 (7–10) right (left) turns. The moment when the centripetal acceleration became zero was defined as the switching time of the right and left turns. The switching time was defined as 0% or 100% of the time.

The time series results of the present study are expressed as mean ± standard deviation (SD). A statistical parametric mapping (SPM) analysis with $t$ values (SPM$\{t\}$) (Pataky, 2010) was used for statistical comparisons of the results of left and right turns within an individual. The SPM analysis was originally developed in the research field of functional magnetic resonance imaging (Penny et al., 2011). On SPM, the family-wise error rate is adjusted to account for the smoothness of the data. Therefore, maintaining the statistical power in the case of non-random time series data is better than other statistical methods such as the Bonferroni method. The level of statistical significance was set at $p < 0.05$. Owing to the small number of skiers, no statistical assessments were applied for inter-individual comparisons.

All analyses, including statistics, were performed using the same numerical calculation software (MATLAB R2019b, MathWorks; Natick, MA).

## Results

Plausible kinematic data were obtained for all skiers (Figure 2). Acceleration data were also obtained (vectors shown in Figure 2). The direction of the acceleration caused by the external force (blue vector in Figure 2) was roughly in line with the normal direction of the sliding surface of the ski.

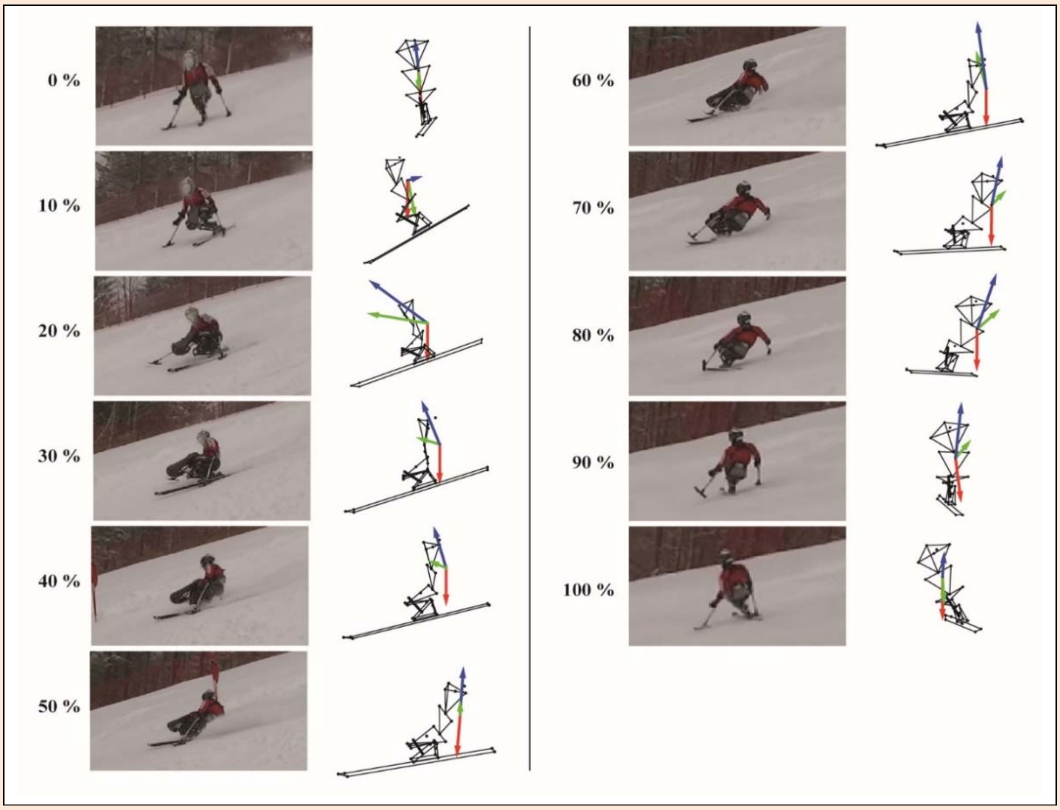


**Figure 2. Typical example of one turn.** The images were obtained from a video camera and stick pictures during a right turn by the LW11 skier is also shown. View angles of the stick pictures were manually adjusted to correspond to the plane of the video images. The vectors pointing upward (blue) and downward (red) respectively represent the acceleration caused by the resultant force of three external forces (ground reaction forces through a ski and two outriggers and air resistance) and the gravity acceleration. The vector pointing toward the center (green) is the sum of the vectors (blue and red vectors). Both 0% and 100% of time indicate the switching instant of the turns. In the turn shown in the figure, the lateral flexion at the chest joint was approximately maximum at the 80%. At that time point, the angles of flexion, lateral flexion, and rotation toward the outside of the turn at the chest joint were 8, 21, and 3 degrees, respectively. The angle of extension at the hip joint was 3 degrees.

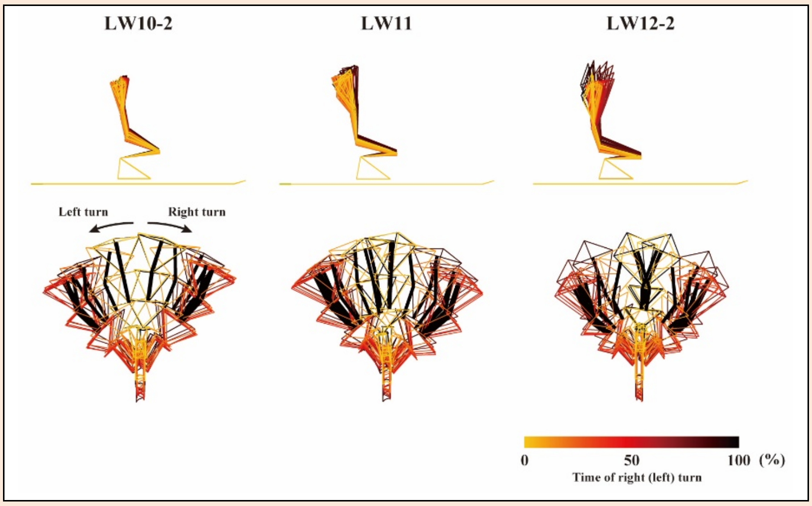


**Figure 3. Stick pictures from the right and back sides of a ski. Stick pictures during the right and left turns are overlaid. The thick line in the figures in the lower panel shows the angulation at the chest joint. Both 0% and 100% of time indicate the switching instant of the right (left) turn. The LW10-2/11 and LW12-2 skiers showed a marked difference in trunk movement in the sagittal plane.**

The average stick pictures during all right and left turns were shown with respect to the ski, at 5%-time interval (Figure 3). Stick pictures from the back sides of a ski were drawn with the tail of the ski as the origin, the normal direction of the plane formed by the direction of gravity and the long axis of the ski as the horizontal direction, and the direction of gravity as the vertical direction. The LW12-2 skier had larger chest and hip joint movements than the LW10-2/LW11 skiers (Table 1 and Figure 3-4a). The hip joint of the LW10-2 skier flexed/extended during skiing, although the skier could not voluntarily flex/extend the hip joint due to the impairment (Figure 4a).

**Table 1.** Maximum angles and angle displacements of the chest and hip joints during right and left turns.

| | | | LW10-2 skier | | LW11 skier | | LW12-2 skier | |
|---|---|---|---|---|---|---|---|---|
| | | | Right turn | Left turn | Right turn | Left turn | Right turn | Left turn |
| Chest | Maximum Angle | Flexion | 25.1 | 16.8 | 4.2 | 11.7 | 37.4 | 34.1 |
| | | Extension | -6.9 | -0.2 | 6.8 | 8.1 | -4.5 | 1.0 |
| | Angle displacement (Flexion + Extension) | | 18.3 | 16.6 | 11.0 | 19.8 | 32.9 | 35.1 |
| | Maximum Angle | Lateral flexion (Turn outside) | 27.1 | 35.4 | 30.1 | 22.6 | 43.9 | 40.6 |
| | | Lateral flexion (Turn inside) | 9.5 | 0.9 | 7.2 | 8.2 | 14.3 | 18.2 |
| | Angle displacement (Outside + Inside) | | 36.6 | 36.3 | 37.4 | 30.8 | 58.2 | 58.8 |
| | Maximum Angle | Rotation (Turn outside) | 17.2 | 7.9 | 8.2 | 17.6 | 20.8 | 17.3 |
| | | Rotation (Turn inside) | 7.5 | 17.2 | 17.2 | 5.8 | 18.6 | 18.3 |
| | Angle displacement (Outside + Inside) | | 24.7 | 25.2 | 25.3 | 23.4 | 39.4 | 35.6 |
| Hip | Maximum Angle | Flexion | 3.6 | 7.9 | 0.9 | 1.7 | -3.1 | 6.3 |
| | | Extension | 6.3 | 2.2 | 1.8 | 1.7 | 11.8 | 7.0 |
| | Angle displacement (Flexion + Extension) | | 9.9 | 10.1 | 2.7 | 3.4 | 8.6 | 13.3 |
| Edging Angle | | | 50.3 | 58.2 | 57.2 | 56.0 | 62.2 | 63.7 |

The three anatomical angles of the chest joint (flexion/extension, lateral flexion, and rotation about the long axis of the lower trunk) were expressed using the Euler angle. The angle displacement shows the sum of the maximum angles in both directions in each anatomical axis of the chest and hip joints. LW10-2/LW11 and LW12-2 skiers have significant differences in the amounts of joint angle displacement. In the case of the LW11 skier, large differences were observed between the right and left turns.

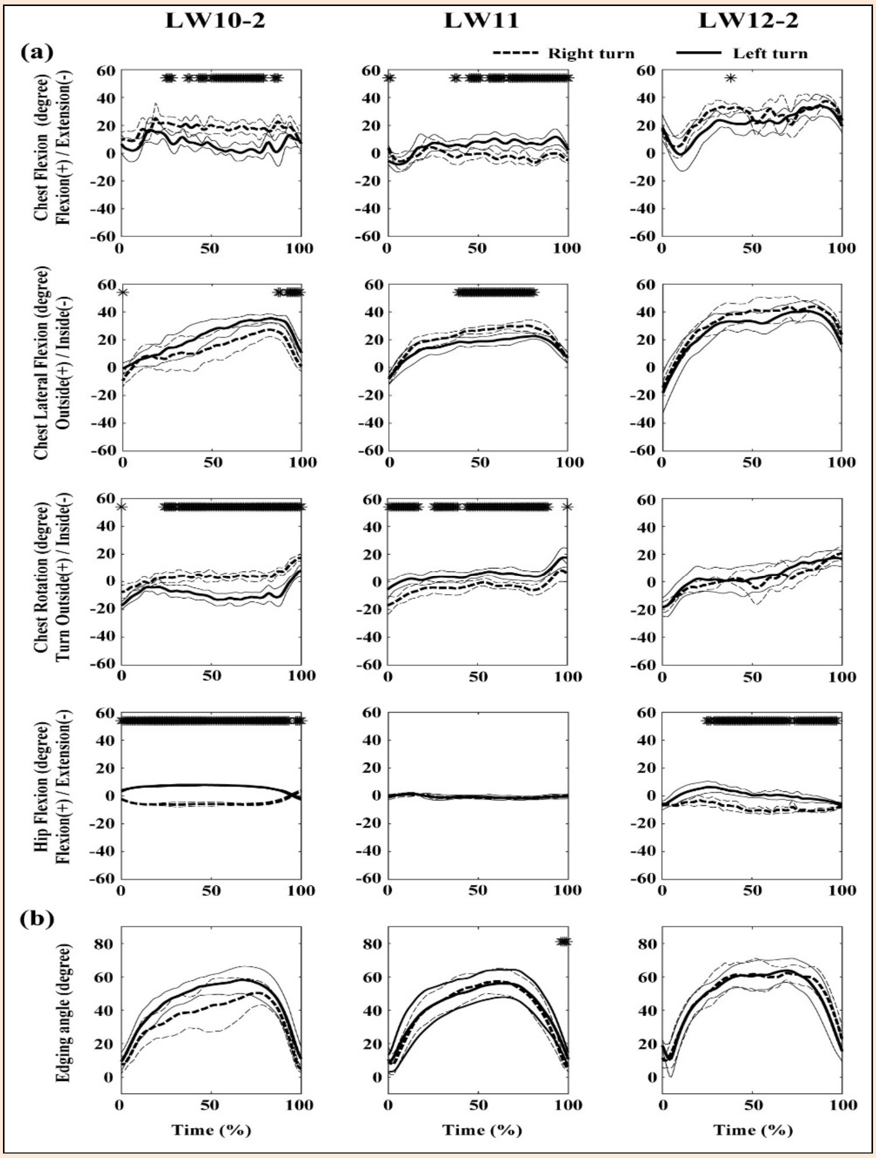


**Figure 4. (a) Chest and hip-joint angles.** Dashed and solid thick lines respectively show the mean values during the right and left turns. The thin line shows the range of 1 SD centered on the mean. The LW10-2/11 and LW12-2 skiers show marked differences in the amounts of joint angle displacement and the maximum joint angle. Owing to the inability of the hip joints to perform voluntary flexion/extension, the variances of the hip flexion angle were smaller than those of the other joint angles in the LW10-2/LW11 skier. The asterisk indicates a significant difference between the right and left turns. **(b) Edging angle.** The chest lateral flexion and the edging angle showed similar trend.

**Table 2.** **Angle displacements of the chest joint during giant slalom (GS) gate running and reference free-skiing.**

| | | Right turn | | | Left turn | | |
|---|---|---|---|---|---|---|---|
| | | GS (degrees) | Reference (degrees) | Difference (%) | GS (degrees) | Reference (degrees) | Difference (%) |
| LW10-2 | Flexion/Extension | 18.3 | 23.3 | 21.5 | 16.6 | 17.6 | 5.7 |
| | Lateral flexion | 36.6 | 37.7 | 3.0 | 36.3 | 38.6 | 6.0 |
| | Rotation | 24.7 | 27.1 | 8.9 | 25.2 | 26.9 | 6.2 |
| LW11 | Flexion/Extension | 11.0 | 13.0 | 15.5 | 19.8 | 15.5 | 27.3 |
| | Lateral flexion | 37.4 | 35.3 | 6.0 | 30.8 | 29.7 | 3.7 |
| | Rotation | 25.3 | 27.1 | 6.8 | 23.4 | 25.2 | 7.0 |
| LW12-2 | Flexion/Extension | 32.9 | 27.1 | 21.3 | 35.1 | 30.9 | 13.7 |
| | Lateral flexion | 58.2 | 50.2 | 16.0 | 58.8 | 55.3 | 6.4 |
| | Rotation | 39.4 | 34.8 | 13.1 | 35.6 | 36.9 | 3.6 |
| Mean (Standard deviation) | | | | 12.4 (6.3) | | | 8.9 (7.1) |

The reference data are angle displacements in free-skiing (middle turn with a slalom ski) and were measured on the same slope among three sit-skiers. The overall trend was similar in both runs, and the mean of the differences was approximately 10%.

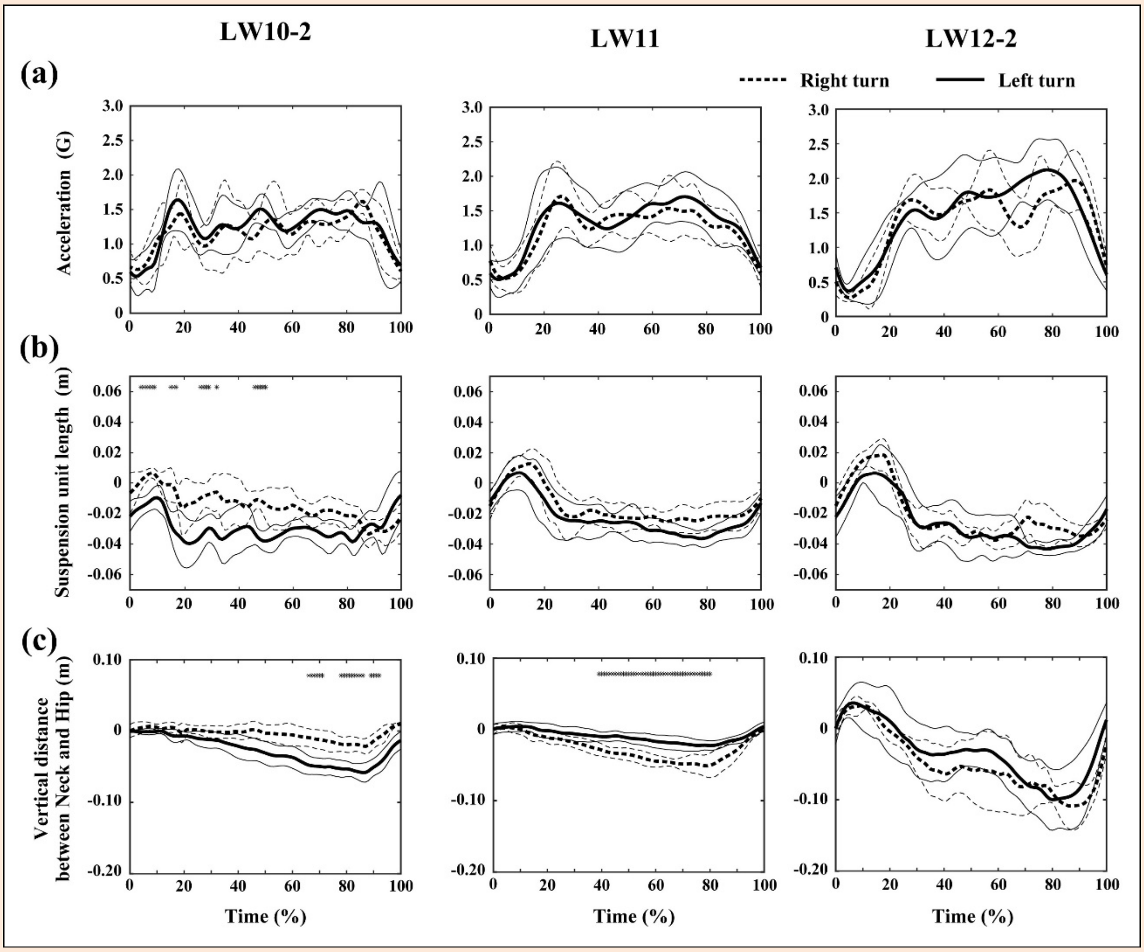


**Figure 5. (a) Acceleration caused the resultant force of the external forces, primarily the ground reaction force through a ski.** During 20–80% of the time, the acceleration remained relatively constant in the LW10-2/LW11 skier. On the other hand, it gradually increased in the LW12-2 skier. The decrease in the acceleration at approximately 10% of the time is a feature unique to sit-skiing. **(b) Length of suspension unit.** A suspension unit lengthened during 0–20% of the time. This would reflect a turn switching technique using the spring built into a suspension unit. **(c) Vertical distance between neck and hip joints.** The normal direction of the ski running surface was defined as the vertical one. The distance at 0% time was shown as the reference distance (0 m).

Angle displacements of the chest joint during gate running in different conditions and during free-skiing on the same slope exhibited similar trends (Table 2). The mean of the differences was approximately 10% and smaller than the angular differences between the LW12-2 and the LW10-2/11 skiers.

For all three skiers, especially the LW10-2 skier, significant differences in the joint motions in the right and left turns were observed (Figure 4a). Thus, the results were shown separately for the left and right turns. One reason of these bilateral asymmetries is suggested to be musculoskeletal asymmetry due to the skier's impairment such as muscle strength (Nyland et al. 1997), lateral obliquity of pelvis (Hobson and Tooms, 1992), and lateral deformity of spine (Mehta et al., 2004); however, these physical characteristics were not measured in the current study. Only the results with common features in both the right and left turns were discussed. Edging angles showed similar trends to the lateral flexion at the chest joint (Figure 4b). Regarding the LW10-2 skier, bilateral asymmetry was observed in edging angle as well as joint angles.

The acceleration caused by the external forces decreased significantly in the initiation phase of a turn (Figure 5a). Thereafter, in the steering phase, the acceleration was maintained at approximately 1.5 (G) in the LW10-2/LW11 skiers or gradually increased up to 2.0 (G) in the LW12-2 skier. Lengthening of the suspension unit was observed in the initiation phase of a turn in all the skiers (Figure 5b). The behaviors of suspension unit length were in antiphase to the acceleration caused by the external forces.

All muscles were continuously activated throughout the run (all turns) (Figure 6). The right (left)-side muscles tended to be activated more during the left (right) turn than during the right (left) turn. No distinct trend associated with the severity of impairment was observed in the magnitude and pattern of muscle activity. The variance of the EMG data was substantial as compared with that of the kinematic data.

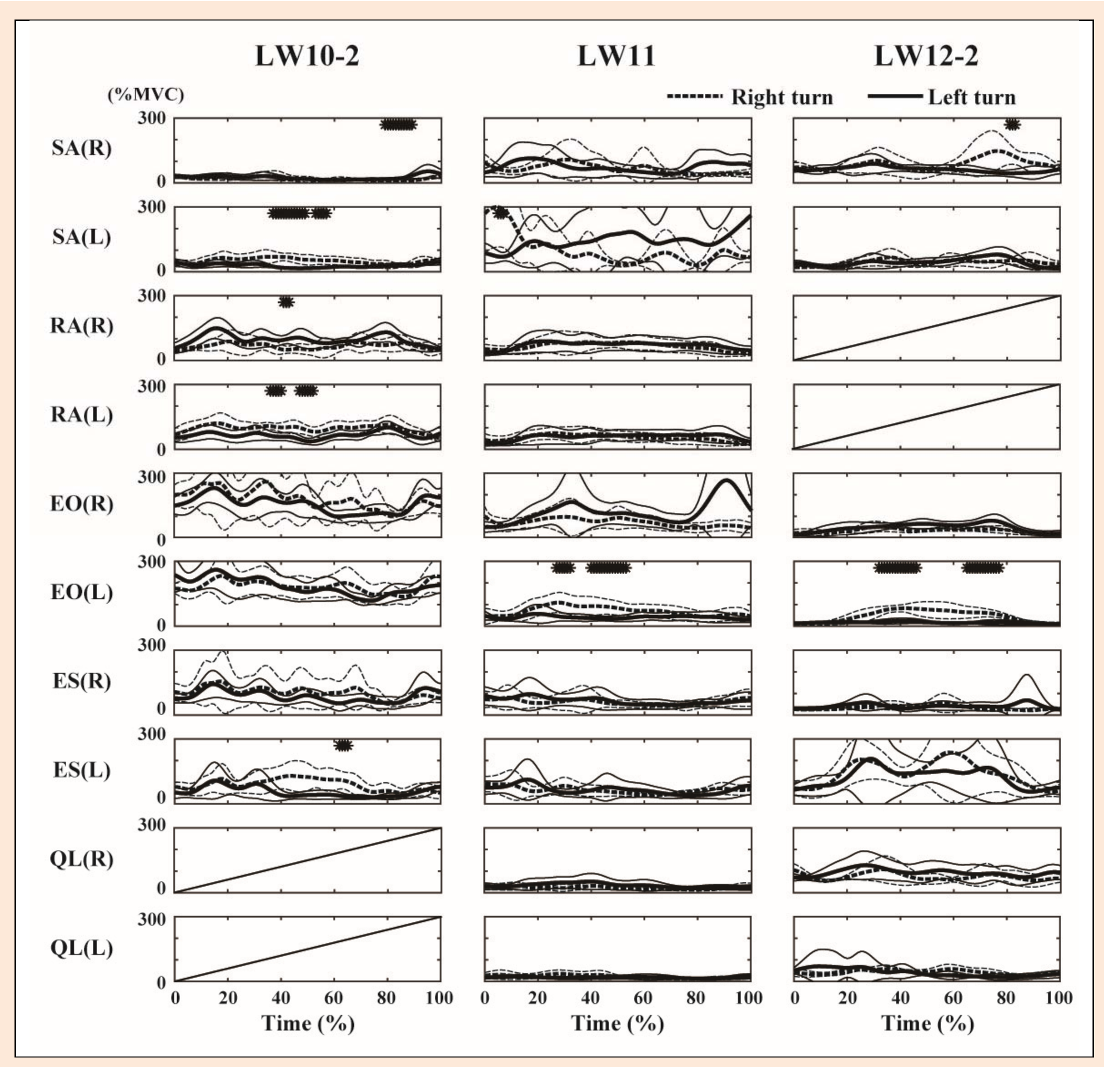


**Figure 6. Electromyographic data.** SA: serratus anterior, RA: rectus abdominis, EO: abdominal external oblique, ES: erector spinae, and QL: quadratus lumborum. The tendency to increase the muscle activities contralateral to the direction of the turn can be observed, although the muscles with a difference in activity between the left and right turns were different among the skiers.

## Discussion

The present study aimed to examine the relationship between the impairment level and the trunk kinematic characteristics during alpine sit-skiing from a classification perspective. The kinematics of the three anatomical axes at the chest joint and the flexion/extension axis at the hip joint were examined in the LW10-2 (more severe impairment class), LW11, and LW12-2 (less severe) skiers, and chest lateral flexion, chest flexion, and hip flexion/extension during sit-skiing were smaller in the LW10-2/LW11 skiers than in the LW12-2 skier. The assessment of the edging angle revealed an identical trend as those with the chest lateral flexion. The acceleration caused by the external forces in the LW12-2 skier increased in the latter half of the turn compared to the LW10-2/LW11 skiers. These results suggest that the insufficient lateral flexion (angulation) caused a reduction in the edging angle, and that the insufficient chest and hip flexion/extension caused a lower loading in the latter half of the turn through smaller vertical movement. Between the LW10-2 and LW11 skiers, no distinct differences in trunk kinematics were found. In the points of muscle activity and suspension length of sit-ski, no distinct differences were found among all classes.

In the LW12-2 skier, the angulation (chest lateral flexion toward the turn outside) reached 40 degrees during sit-skiing (Figure 4a, Table 1). This angle is comparable to the total range of lateral flexion in the thoracic and lumbar spinal regions (Schünke et al., 2014). These facts reveal that the entire range of motion is used in lateral flexion during sit-skiing. Chest lateral flexion was smaller in the LW10-2/LW11 skiers with trunk impairment than in the LW12-2 skier without trunk impairment, and the edging angle was also smaller (Figure 4b, Table 1). These results indicate that the insufficient angulation due to lateral flexion limitation resulted in a lower edging angle. Since the maximum edging angle determines the minimum radius of the carving turn that a skier can make (Reid et al., 2020), the negative impact of decreased edging angle on race performance is critical. Future classification research should aim to evaluate the relationship between lateral flexion and ski performance in greater detail.

Contrary to the severity of impairment, the LW10-2 skier had greater lateral flexion than the LW11 skier (Table 1). Scapular movement may have influenced on this. Because a sensor on upper trunk was attached by a straps of backpack type, the lateral flexion during skiing partially included the scapular movement over the thorax as well as the spine. To assess this point, the maximum lateral flexion of spine (the angle of the cervical spine relative to the pelvis) at stationary on a sit-ski was additionally measured for both skiers, and was found to be six degrees smaller for the LW10-2 skier than for the LW11 skier (LW10-2 and LW 11 skier is 19 and 25 degrees, respectively). This result suggests that the scapula moved more significantly during the LW10-2 skier's skiing than during the LW11 skier's skiing. If the lateral flexion is to be used as a measure of activity limitation, it may be important to use a measuring method that reflects the characteristics of the spine only.

The maximum joint angles in the LW10-2/LW11 skiers showed no clear trend between classes (Table 1). In the GS, the difference in the scaling factor of race time (WPAS Factor List 2021/2022) is approximately 0.008 between LW10-2 and LW11, 0.03 between LW11 and LW12-2. Assuming the factor as the average sit-skiing performance of each class, the difference in sit-skiing performance between LW10-2 and LW11 is a quarter of that between LW11 and LW12-2. It may be reasonable that no clear trend was observed compared to the difference between LW12-2 and LW10-2/LW11. These results indicate that when classifying based on controllable regions in the trunk, such as LW10-2 and LW11 classes, a high-resolution method is required for activity limitation assessment.

Chest rotation, unlike flexion/extension and lateral flexion, showed no distinct difference among the classes (Table 1). A possible reason for this is that rotation during sit-skiing was only about half of the range of motion in the rotational axis of the spine (Schünke et al., 2014). Additionally, the influence of lower trunk impairment and trunk fixation by the backrest of the bucket seat on the range of motion of trunk rotation might have been smaller than on that of lateral flexion and flexion/extension, since the thoracic and cervical spines are the primary contributors to spinal rotation and the contribution of the lumbar one is low. The amount of chest rotation may be less important as a measure of activity limitation, since maximum chest rotation during sit-skiing is less affected by the severity of the impairment. However, in a skier with an upper trunk impairment, such as the LW10-1 skier, further research is required.

The difference in hip flexion/extension between the LW11 and LW12-2 skiers (Table 1) would be attributed to whether or not the hip joint is impaired. Conversely, comparable hip flexion/extension was observed in the LW10-2 skier (Figure 4a). Since skiers in the LW10-2 class cannot voluntarily move the hip joint, a passive movement may accompany the change in effective slope angle that occurs during the turn (LeMaster, 2009). However, it is unlikely to be the cause, as the hip movement was different in the left and right turns and no movement was observed in the LW11 skier, who, similar to the LW10-2 skier, cannot voluntarily move the hip joint. We have deemed it reasonable to regard this as a passive movement accompanying active movements such as voluntary flexion/extension at the chest joint. This fact indicates that the presence or absence of joint motion during a turn does not indicate whether the joint can be voluntarily moved or not. In the classification process, classifiers may conduct movement observation in competition to ensure consistency with the impairment and physical assessments (World Para Alpine Skiing Classification Rules and Regulations, 2017; Ungerer, 2018). This finding should be considered during the observation.

Understanding the profiles of external forces in each class provides a basis for clarifying the relationship between impairment and skiing performance, because a skier's trajectory and speed are determined by regulating the magnitude and direction of ground reaction force through the ski (Reid, 2010). The acceleration caused by the external forces (primarily the ground reaction force through a ski) (blue vectors in Figure 2) during turns in the LW10-2/LW11 skiers appeared almost constant in the steering phase (Figure 5a). This is consistent with the result obtained by Goll et al. (2018). As for the LW12-2 skier the acceleration gradually increased until the latter half of the steering phase unlike the results of Goll et al. (2018). One reason for this may be due to the difference in the impairment level of the skiers (Goll et al., 2018: LW12-1 vs. the present study: LW12-2). Since the primary difference between the LW12-2 and the other class skiers is the ability to fully activate the hip muscles, this may have affected the difference in acceleration in the latter half of the turn. Whether or not the hip can be fully activated may be important in terms of activity limitation. From a kinematic point of view, the following points could have influenced the acceleration; skier's motion on the sit-ski's seat, ski turn radius, average speed, speed change during the turn, suspension settings. Of these, it is inferred that the former two had an influence.

In standing skiers, the skier's vertical movement during the latter half of the turn is known to change the ground reaction force through a ski and that the skier uses this force change to control the turn. The LW12-2 skier's vertical movement was greater than that of LW10-2/LW11 skiers (Figure 5c). This suggests that LW12 skiers, who could largely move on the sit-ski's seat (Upper panel of Figure 3), controlled their turns during the latter half of the turn by using the vertical movement of the upper body with both chest and hip flexion/extension (Figure 4a). Enhanced active control may have led to the increase in the acceleration. As for turn radius, Spörri et al. (2016) compared the estimated ground reaction force in GS using skis with different side-cuts and revealed that the ground reaction force during the latter half of the turn was affected by the turn radius. In the present study, the edging angle of the LW12-2 skier was larger than that of the LW10-2/LW11 skiers. Assuming that the ski tends to carve more in the latter half of the turn (Spörri et al., 2016), that is to say, the turn radius in the latter half of the turn is determined to some extent by the edging angle (Reid et al., 2020), this might have resulted in a smaller turn radius in the latter half of the turn and thus a greater acceleration. The speed is also another factor that affects the acceleration. First, the difference in average speed may contribute as a factor; however, if the difference exists, acceleration should change during all phases of the turn. Since the increase in acceleration is limited in the latter half of the turn, it is unlikely that the difference is a factor. Second, it is also possible that speed change (braking) was greater in the latter half of the turn in the LW12-2 skier. However, this is also unlikely because skiers in the LW12-2 class are generally faster, and speed change during the latter half of the turn was shown to be small in GS (Gilgien et al., 2015; Spörri et al., 2016). As will be mentioned in the next paragraph, the relationship between acceleration and suspension length is strong, so differences in sit-ski settings are also a possible factor. However, it is suggested that the effect of suspension setting is small, since there was a difference in the increase in acceleration despite the similar suspension length profiles of the LW11 and LW12-2 skiers. From the points discussed above, we believe the former two points are the most likely factor. Since the two points are associated with chest lateral flexion, chest flexion, and hip flexion/extension, the assessment of activity limitation in those joint motions might be important in classification.

The behaviors of a suspension unit length were in antiphase to the acceleration caused by the external forces. This would reflect a turn-switching technique that removes the load on a ski (so-called unweighting (LeMaster, 2009)) by lifting the body using the elastic energy stored in the spring built into the suspension unit. This technique is unique to sit-skiing, which differs from standing skiing. The suspension during the initiation phase of the right turn in the LW10-2 skier was not as compressed as during that of the left turn or in the LW11/LW12-2 skiers. The difference was considered to be due to not only the impairment level, but also due to the suspension settings, individual differences in skiing skill, and their interaction. For example, along with differences in the compression length of suspension, there were also differences in the movement of skiers such as smaller lateral flexion at the chest, smaller edging angle, and more backward trunk tilt at the hip. These results indicate a complicated relationship between sit-ski mechanics and skier's motion. In the present study, it was not possible to distinguish the effects of each factor or the interactions among factors. Considering that sit-skiing uses one of the most specialized equipment among adaptive sports (De Luigi and Cooper, 2014), it is estimated that the influence of impairment on sit-skiing performance varies depending on the configuration and settings of sit-ski. Further study is important in terms of classification.

No muscle activity associated with severity of impairment was observed from the EMG results, both in terms of magnitude and pattern of muscle activity (Figure 6). Additionally, large variations were observed in the results. These results show that the usefulness of EMG information during sit-skiing is low in classification. Additionally, considering the effort required to measure EMG and the need for specialized devices, the inclusion of EMG in the regular classification process would not be recommended at this stage.

Owing to the small number of skiers, the results of the present study could not be generalized. However, the number of measured turns was large for each skier. In addition, all the three skiers were Paralympic medalists; that is, they had superior skills and many common characteristics. These facts indicate that the results and findings of the present study are sufficiently useful as the basic knowledge that contributes to evidence-based classification in alpine sit-skiing, even considering the limitations of the small number of subjects and the lack of comparisons between inter-individuals with statistical tests. However, to improve the certainty of the results, more subjects must be included in future studies. Another limitation is that the data of the skiers were measured under different slopes and gate settings. Although the effect was not significant enough to change the discussion of the current study (Table 2), it is desirable to measure with the same slope and gate settings. We recognize that this can be achieved in the future through improvements in measurement equipment (especially EMG) and protocols. This would be essential to examine the differences between LW10-2 and LW11 classes.

## Conclusion

Chest lateral flexion, chest flexion, and hip flexion/extension angle during sit-skiing were decreased due to impairment. Additionally, it was suggested that the insufficient lateral flexion (angulation) caused a decrease in the edging angle, and that the insufficient chest and hip flexion/extension caused a lower loading in the latter half of the turn through smaller vertical movement. Since edging angle and loading are key factors in ski control, the three joint motions could be measures of sport-specific activity limitation in sit-skiing classification.

Between the LW10-2 and LW11 skiers, no distinct differences in trunk kinematics were found. Assuming the scaling factor of race time as a measure of skiing performance, a possible reason is that the difference in skiing performance the LW10-2 and LW11 skiers is considerably smaller than that between the LW11 and LW12-2 skiers. This result indicates that studies examining differences between classes with more severe impairments require a large number of subjects and a method with high statistical power. There were no distinct differences among classes in the results of trunk rotation, muscle activity (electromyography), or suspension length, and therefore, this information would be less important in classification.

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## Key points

- Chest lateral flexion, chest flexion, and hip flexion/extension angle could be measures of sport-specific activity limitation in sit-skiing classification.
- Classification studies on the sit-skiers with more severe impairments might require a large number of subjects and methods with high statistical power.
- Information on muscle activity (electromyography) would be less important in classification.

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