KJSB

Korean Journal of Sport Biomechanics 2016; 26(4): 361-367
http://dx.doi.org/10.5103/KJSB.2016.26.4.361
http://e-kjsb.org eISSN 2093-9752

ORIGINAL

# Comparison of Three-dimensional Kinematic Changes of the Lower Extremity between the Two Different Braking Distances of Snowplow in Alpine Skiing

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**Received : 21 September 2016**
**Revised : 26 November 2016**
**Accepted : 06 December 2016**

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**Objective:** The aim of this study was to compare three-dimensional kinematic changes of the lower extremity between the two different braking distances during snowplow in alpine skiing.

**Method:** Six alpine ski instructors (age: 25.3 ± 1.5 yr, height: 169.3 ± 2.9 cm, weight: 66.2 ± 5.9 kg, career: 4.2 ± 2.9 yr) participated in this study. Each skier was asked to perform snowplow on the two different braking distances (2 and 4 m).

**Results:** Snowplow and edging angles ($p$ = .006 and $p$ = .005), ankle adduction and inversion ($p$ = .033 and $p$ = .002), knee extension ($p$ = .003), and hip abduction and internal rotation ($p$ = .043 and $p$ = .006) were significantly greater in the 2 m than in the 4 m braking distance.

**Conclusion:** Based on our results, we suggest that skiers should make greater snowplow and edging angles on the shorter braking distance. In this situation, ankle joint adduction/inversion angle and hip joint internal-rotation make greater snowplow angle, and hip joint abduction make greater edging angle. In addition, greater knee joint extension angle may lead to more posteriorly positioned center of mass.

**Keywords:** Alpine ski, Snowplow, Braking distance, Three-dimensional analysis, Braking technique

## INTRODUCTION

Alpine skiing began as a means of transportation in the Alpine mountains, and now it has developed into a sport of rapidly sliding down steep snowy surfaces. Despite the difficulties of measurement due to the environmental effects of cold and inclined snow surfaces, studies on alpine skiing have been conducted in various aspects through the development of precise measurements over many years to overcome such challenges. However, most studies have been conducted to improve the performance of elite alpine skiers (Gilgien, Crivelli, Spörri, Kröll & Müller, 2015; Supej, Hébert-Losier & Holmberg, 2015). Other kinematic studies were conducted on intermediate and expert skiers in the inter-ski area to develop new skiing skills and teaching methods to improve the skills of general skiers (Kim, Jeon et al., 2014; Kim, Yoo et al., 2014; Müller et al., 1998). In South Korea, although the annual number of skiers has exceeded 6.6 million and most skiers are inexperienced, most ski instructors have trouble in relying too much on qualitative lesson guidelines to improve the skills of ski beginners, as not many quantitative studies on skiing in novice skiers exist (The Ministry of Culture, Sports and Tourism [MCST], 2008).

Alpine skiers have a primary purpose in controlling speed and direction, as they slide down snow-covered mountains, while beginners who are new to alpine skiing learn how to snowplow (or *pflug fahren*), a basic braking technique to reduce speed (Hintermeister, O'Connor, Lange, Dillman & Steadman, 1997; Kuna, Dzajic & Males, 2015). Snowplow is a technique that involves wearing the ski plates on both feet and forming an "A" shape, with a narrow front and wide rear, to generate constant resistance to the inertia caused by propulsion and usually used at slow speed or mild slopes as short as 2~4 m, whereas the ski plate is parallelized and braked by using side sliding at higher speeds or steep slopes (Lind & Sanders, 2004). As the snowplow uses the edge of the ski plate when sliding down, the surface-plowing force at the edge of the ski plate controls the speed. When controlling the speed by using snowplow, the larger the edging by the size of the A shape, the greater the braking force due to the plowing force. Therefore, when teaching how to snowplow to beginners, the snowplow and edging angles between the two ski plates must be increased to increase the plowing force; it is common to ask them to bend and gather their knees (Lind & Sanders, 2004). However, the guideline of teaching snowplow was based on the experiential knowledge of the expert alpine skiers

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**Figure 1.** Experimental setup (left) and the two different snowplow braking distances (right).

and was not fully understood by quantitative analysis.

Alpine ski injuries are mainly caused by falls during sliding or by accidental contact with other skiers or obstacles due to steering or braking errors (McBeth, Ball, Mulloy & Kirkpatrick, 2009). Especially, beginners often experience accidents that cause anterior cruciate ligament damage, as they fail to brake while snowplowing or lose balance to the back of the ski plate (Ettlinger, Johnson & Shealy, 1995). For the quantitative analysis of the basic techniques to prevent such accidents, Kim (2004, 2006) reported on the lower body joint angle and change in the body center via comparative analysis of the snowplow motions between expert and unskilled skiers. Although different braking techniques are required depending on the braking distance to prevent accidents, which can occur instantaneously, the kinematic factors required for braking distance control are difficult for skiers to be generalized because the variable for braking distance was not considered. Moreover, although the three-dimensional (3-D) motion of lower extremities in alpine skiing directly changes the braking force generated between the ski plate and the snow surface (Klous, Müller & Schwameder, 2012; Koo, Lee, Kweon, Hyun & Eun, 2014; Müller & Schwameder, 2003), 3-D kinematic analysis that considers the degree of freedom in each lower limb joint was not performed. Therefore, the purpose of this study was to investigate the 3-D kinematic differences in the lower limb between the braking distances of 2 and 4 m when beginners perform snowplow to acquire the correct snowplow motion required to control the braking distance.

## METHODS

### 1. Participants

The subjects of this study were six instructors of the Korea Ski Instructors Association who could ideally perform snowplow. All the subjects who participated in the study were male and had no musculoskeletal system abnormalities (age: 25.3 ± 1.5 yr, height: 169.3 ± 2.9 cm, weight: 66.2 ± 5.9 kg, experience: 4.2 ± 2.9 yr). All the subjects received a full explanation of the experimental procedure before participating in the experiment, and the experiment was conducted only with the instructors who agreed to participate by providing written consent.

**Figure 2.** Marker setup for the ski plate, foot, and shank.

### 2. Measurements

All skiers spent enough time for warm-up and practicing snowplow, and then stopped by snowplowing on a groomed ski terrain with an average slope of -10°. As braking by snowplowing is performed at a slower speed in alpine skiing with the typical braking range of 2~4 m, 2 m was set as a sudden braking distance and 4 m as a normal braking distance. All the skiers performed three trials per braking distance (Figure 1). The execution range consists of 20 m of run phase and 2 or 4 m of braking phase, and the entry speed in the runway was controlled at 3.5 m/s by using timing lights (Seed Tech, Korea). Eleven infrared cameras (sampling rates, 100 Hz; Oqus 300, Qualisys, Sweden) were installed for motion analysis. A total of 37 reflection markers were used to model the lower limb, with a marker attached to each joint

point and segmental end, and a cluster to the center of each segment. In addition, eight reflective markers were attached to the left and right ski plates to model the ski plate (Figure 2).

## 3. Data processing

Visual3D (C-Motion, USA) and Matlab R2009b (MathWorks, USA) were used to perform motion analysis of the reflection markers collected through infrared cameras. The Butterworth second-order low-pass filter was used to remove the noise from the 3-D coordinates of the reflective markers converted by the nonlinear transformation (NLT) method with the set cut-off frequency of 12 Hz.

The variables were snowplow angle, edging angle, and 3-D angles of the ankle, knee, and hip joints. As snowplow braking is executed to continuously resist the inertia generated by the propulsive force, the average value during the braking phase was calculated. The average of each subject's three attempts was chosen as his representative value. The 3-D angles of all segments and joints were calculated by using the Cardan XYZ rotation sequence (*x*: mediolateral, *y*: anteroposterior, *z*: vertical) from the joint coordinate system after positioning the unit vector on the segment center based on the 3-D marker information of each segment and joint obtained during the standing trial (Cole, Nigg, Ronsky & Yeadon, 1993). All lower limb joint angles were defined as the angle of the distal segment relative to the proximal segment. The boot movement represents the foot movement with the foot fixed on the boot, and the ankle joint movement was defined as the relative angle with the cluster attached to the lower leg. Moreover, the snowplow angle was defined as the included angle in the vertical axis when the left and right ski plates form an A shape, and the edging angle as the angle in the longitudinal axis of the ski plate (Figure 3).

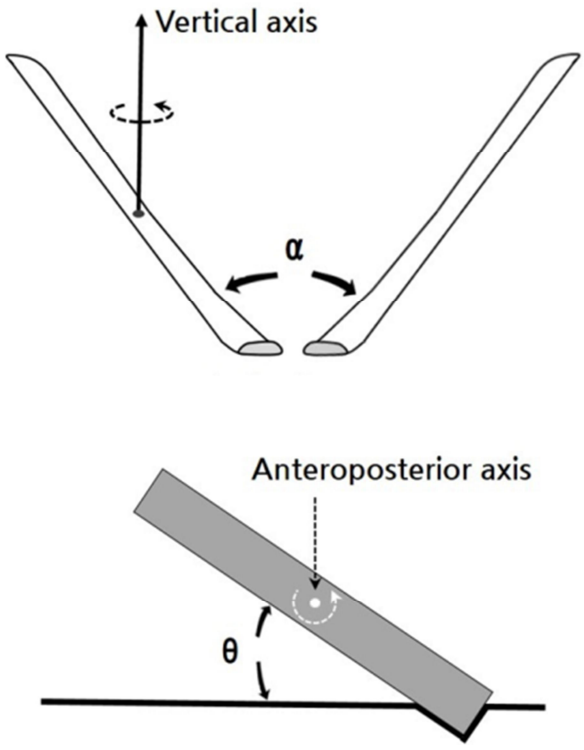


**Figure 3.** Definition for ski-plate angle. $\alpha$ is the snowplow angle (left), and $\theta$ is the edging angle (right).

## 4. Statistical analysis

To find the significant differences between the 2 and 4 m braking distances by using the snowplow, all the variables were analyzed with a paired *t* test on the mean value of the data collected during the braking phase. The significance level was set to $\alpha = .05$.

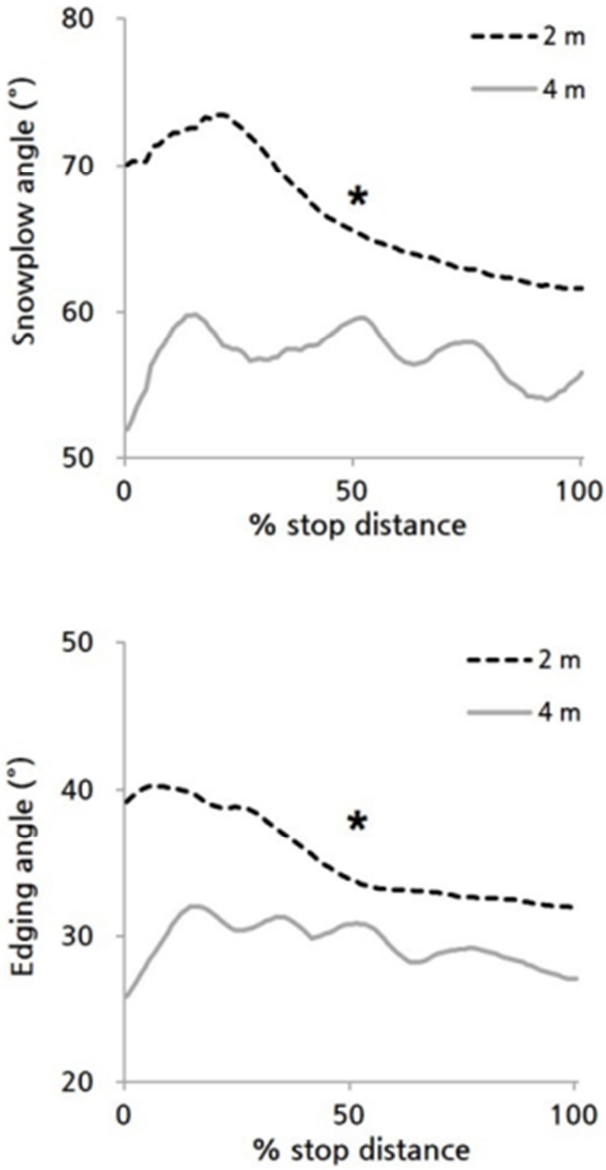


**Figure 4.** Ensemble-averaged snowplow and edging angles are shown between the 2 and 4 m snowplow braking distances. All data were time normalized to 100% of the braking distance differences. Statistical significance effects were calculated by using a paired *t* test. The asterisk indicates a significant statistical difference between the two conditions.

## RESULTS

### 1. Ski plate angle

The snowplow angle was 66.7° ± 3.1° at the 2 m braking distance and 57.3° ± 3.93° at the 4 m braking distance, significantly larger at the 2 m than at the 4 m distance ($t$ = 4.610, $p$ = .006; Figure 3). The edging angle was 35.4° ± 3.1° at the 2 m braking distance and 29.5° ± 4.7° at the 4 m braking distance, significantly larger at the 2 m than at the 4 m braking distance ($t$ = 4.829, $p$ = .005; Figure 4).

### 2. Lower extremity joint angle

#### 1) Ankle joint angle

The adduction angle of the ankle joint was 11.6° ± 4.9° at the 2 m braking distance and 9.1° ± 6.0° at the 4 m braking distance, significantly larger at the 2 m than at the 4 m braking distance ($t$ = 2.923, $p$ = .033). The inversion angle of the ankle joint was 12.9° ± 2.4° at the 2 m braking distance and 12.2° ± 2.2° at the 4 m braking distance, significantly larger at the 2 m than at the 4 m braking distance ($t$ =

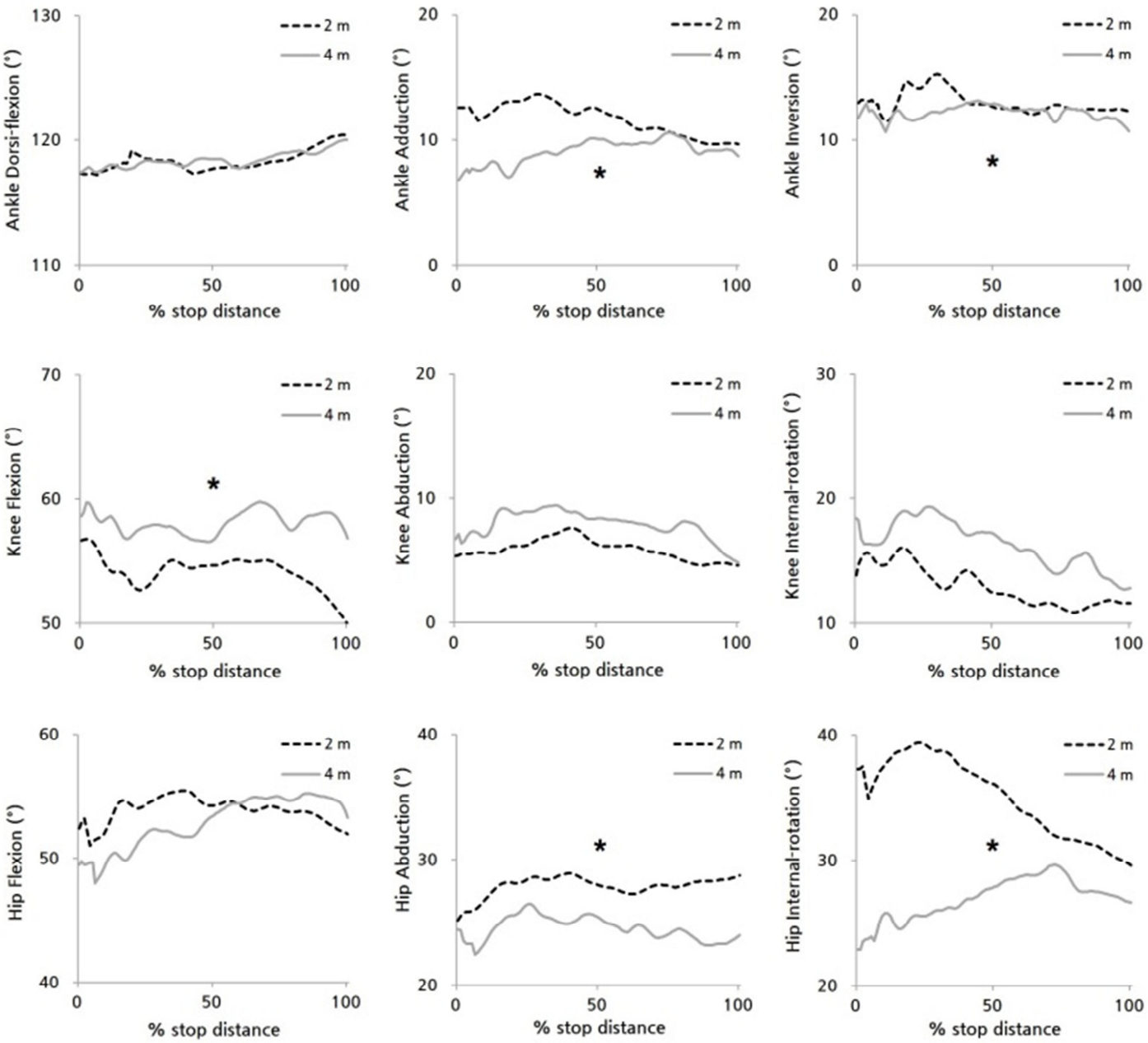


Figure 5. Ensemble-averaged lower extremity angles are shown between the 2 and 4 m snowplow braking distances. All data were time normalized to 100% of the braking distance differences. Statistical significance effects were calculated by using a paired $t$ test. The asterisk indicates a statistical difference between the two conditions.

5.884, $p$ = .002). On the other hand, the ankle dorsiflexion angle was 118.4° ± 4.4° at the 2 m braking distance and 118.4° ± 3.8° at the 4 m braking distance, without significant difference between the braking distances ($t$ = -.052, $p$ = .961; Figure 5).

### 2) Knee joint angle

The flexion angle of the knee joint was 54.2° ± 3.7° at the 2 m braking distance and 58.1° ± 4.2° at the 4 m braking distance, showing a significantly smaller flexion (larger extension) at the 2 m than at the 4 m braking distance ($t$ = -5.884, $p$ = .003). The abduction angle of the knee joint was 5.9° ± 3.7° at the 2 m braking distance and 7.9° ± 8.0° at the 4 m braking distance, without significant difference between the braking distances ($t$ = -1.032, $p$ = .349). The internal rotation angle of the knee angle was 13.0° ± 8.4° at the 2 m braking distance and 16.4° ± 3.8° at the 4 m braking distance, without significant difference between the braking distances ($t$ = -1.453, $p$ = .206; Figure 5).

### 3) Hip joint angle

The abduction angle of the hip joint was 27.9° ± 4.4° at the 2 m braking distance and 24.5° ± 2.1° at the 4 m braking distance, significantly larger at the 2 m than at the 4 m braking distance ($t$ = 2.699, $p$ = .043). The internal rotation angle of the hip joint was 35.0° ± 3.2° at the 2 m braking distance and 27.0° ± 6.7° at the 4 m braking distance, significantly larger at the 2 m than at the 4 m braking distance ($t$ = 4.644, $p$ = .006). On the other hand, the flexion angle of the hip joint was 53.9° ± 12.0° at the 2 m braking distance and 53.0° ± 7.2° at the 4 m braking distance, without significant difference between the braking distances ($t$ = .372, $p$ = .725; Figure 5).

## DISCUSSION

Alpine skiing is a sport of sliding on inclined snow surfaces in a fast pace. Various techniques have been developed based on braking and turning through the control of the ski plate. In case of recreational skiers who perform alpine skiing for the first time, the ability to cope with various situations by learning how to snowplow to prevent collisions with other skiers or obstacles and accidents caused by falls is essential. Moreover, such alpine skiing technique requires coordination between various muscles (Hintermeister et al., 1997). Also, the 3-D motion of the lower limb joints occurs in a complex manner. Therefore, in this study, we aimed to investigate the quantified 3-D kinematic patterns so that beginner skiers can learn the correct snowplow motion required to control the braking distance.

Snowplow generates braking force from the resistance between the snow surface and the edge because of the plowing force of the two ski plates forming an "A" shape (Lind & Sanders, 2004). The greater the A shape—that is, the larger the snowplow angle defined by the angle between the two ski plates—the bigger the plowing force. The snowplow angle is determined by the extent of how much the tip and tail on both ski plates are widened. The correct A-shape is when only the tails are spread while the tips are closer together. Thus, the snowplow angle is determined by the distance between the tails with the tips drawn close. The results of this study showed that the snowplow angle must become larger by broadening the distance between the tails when more braking force is required (Kim, 2004, 2006).

The plowing force also increases when the edging angle on both ski plates increases (Lind & Sanders, 2004). The plowing force is generated when skidding occurs on the side of the ski plate, which can be defined as the friction force. The friction force is generated in between the ski plate edge and the snow surface, and can be divided into penetration and shear forces (Mössner et al., 2014; Figure 6). When skidding occurs, the penetration depth increases as the edging angle increases because the penetration force of the ski plate acting vertically on the snow surface becomes larger. Therefore, the shear force increases as well owing to the coefficient of friction ($\mu$) increasing proportionally to the penetration force (Mössner, Nachbauer, Innerhofer & Schretter, 2003). In

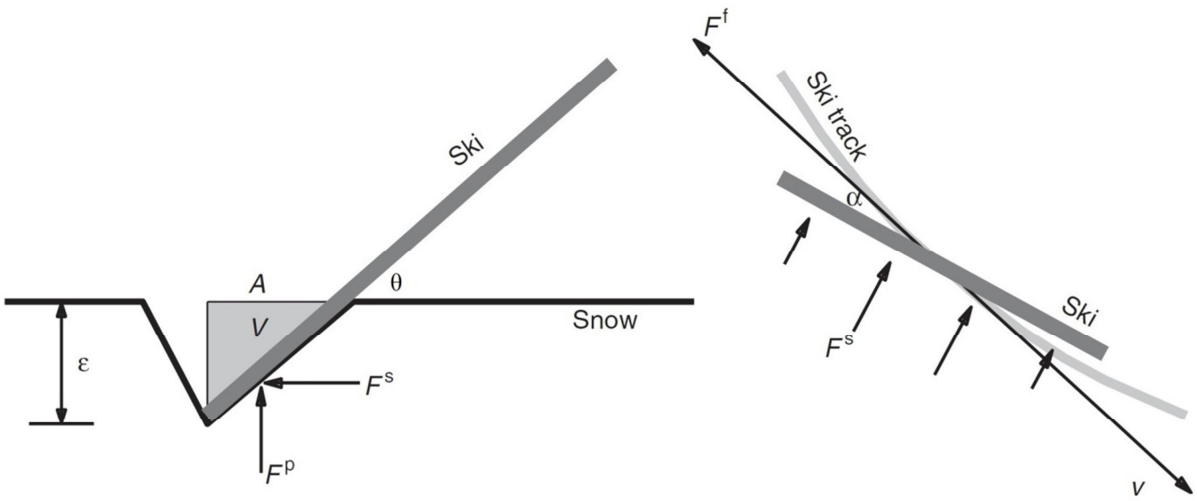


**Figure 6.** Snow contact forces acting on the ski. $F^p$, penetration force; $F^s$, shear force; $F^f$, friction force; $\varepsilon$, penetration depth of the ski edge; $\theta$, edging angle; $\alpha$, attack angle of the ski; $V$, the displaced volume of snow by the ski; and $A$, contact area between the ski and the snow projected to the undisturbed snow surface of the hill (Mössner et al., 2014).

other words, the friction force between the ski plate and the snow surface increases as the edging angle becomes larger. Greater friction force needs to be generated while increasing the edging angle if the braking distance becomes shorter.

Complex 3-D motion of the various leg joints is required to adjust the snowplow and edging angles by using a ski plate. The kinematic analysis of the ankle joints in this study showed that the shorter the braking distance, the more adduction and inversion of the ankle occurs during snowplow. To control the ski plate by using the ankle joint, the ankle must perform eversion to increase the edging angle or perform adduction to increase the snowplow angle. However, Kim (2004, 2006) reported that the edging angle during snowplow is determined by the motion of the knee and hip joints, not by the ankle motion alone. Furthermore, because the ankle movement occurs on the oblique axis as the axis of rotation, either adduction and inversion, or abduction and eversion occur at the same time (Neumann, 2013). Based on the ankle movement not contributing to the edging angle and on abduction and eversion happening at the same time on the oblique axis as its rotation axis, we can infer that the shorter the braking distance during snowplow, the greater the contribution of the ankle joint to the snowplow angle than to the edging angle.

In the Alpine skiing area, the knee joint is generally known to undergo flexion and internal rotation simultaneously to increase the edging angle during snowplow (Lind & Sanders, 2004). However, our study results showed that the extension on the knee joint became larger as the braking distance decreased and that no movement was made to increase the edging angle by using the knee joint. Kim (2004, 2006) reported that because the body center moves toward the back as the braking distance shortens during snowplow, the load is transferred to the tail of the ski plate during the process of increasing the snowplow angle. Therefore, the extension of the knee joint observed in this study at the short braking distance can be considered an effort to move the body center backward to transmit the load to the tail part.

During snowplow, the 3-D motion of the hip joint seems to be the main movement that determines the edging angle of the ski plate and the snowplow angle. The study result showed that the shorter the braking distance, the more abduction and internal rotation occurs at the hip joint at the same time. As the abduction of the hip joint has a larger range of motion on the frontal plane (hip-joint abduction: average of approximately 40°) than the ankle or knee (Neumann, 2013), it is what mainly increases the edging angles on the ski plate (Kim, 2004, 2006). Furthermore, the internal rotation of the hip joint has a larger range of motion as well on the transverse plane (hip joint internal rotation: average of approximately 35°), which shows that the internal rotation of the lower limb is what mainly increased the snowplow angle.

The existing snowplow training for new skiers only covers the operation of the ski plate. Based on our study results, training using movements of the hip, knee, and ankle joints can help a beginner skier control the ski plate and perform the technique. When a novice skier learns the snowplow braking technique, the next step is to learn how to do a snowplow turn (*pflug bogen*). As the snowplow turn must be operated while maintaining the snowplow position, the 3-D kinematic analysis of this study will be greatly useful for establishing quantitative training guidelines in the future.

## CONCLUSION

This study quantitatively compares the 3-D kinematic patterns in the lower limb for two braking distances during snowplow. The experiment was conducted with six ski instructors, and braking using snowplow at a braking distance of 2 or 4 m was used to analyze the edging angle of the ski plate, the snowplow angle, and the 3-D angles of the ankle, knee, and hip joints. The edging and snowplow angles appeared to be significantly larger at the braking distance of 2 m than at 4 m, as well as adduction and inversion of the ankle joint, extension of the knee joint, and abduction and internal rotation of the hip joint.

Based on our study results, the following conclusions were obtained: In the braking attempt using snowplow, at the shorter braking distance, the edging angle must be increased by increasing the abduction of the hip joint, the snowplow angle should be larger for a greater braking force, and the knee joint must be extended to transfer the load to the tail of the ski plate.

The follow-up of this study should include quantitative analysis of various biomechanics experiments for enhancing other techniques such as the snowplow turn.

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