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Design of Ski Boots for Alpine Ski Racing Based on Leg Frame of the Skier*

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Abstract

A ski boot is important to make progress in ski turning technique as an interface between a skier and a ski. Especially in alpine ski races, suitability of design of the boots for racers becomes more important to achieve accurate and quick lean of the leg in ski turns. This study is aimed at building a new design concept of a ski boot that can improve the results of alpine ski races. In this paper, new design of an upper shell of a ski boot that was adjusted to the features of the frame of alpine ski racers was experimentally examined. As a result, it was demonstrated that a front and a rear part of the upper shell of a ski boot should be separately adjusted to the length of a shank of each player for well-balanced quick lean of the leg in the ski turn. Finally, the effect of new design of an upper shell was examined in giant slalom and slalom tests by Japanese alpine ski racers of the first rank. Consequently, the results showed that lean angle during turns was increased and finish time was shortened when the skiers wore the newly designed boots.

Key words: Ski Boot, Upper Shell, Alpine Race, Quick Lean, Shank Length

1. Introduction

Alpine ski racing is a competition in which the skier who skis down the course in the fastest time is the winner. Ski base preparation and edge tuning as well as turning techniques and strategy of the skier are important for achieving a fast time. Another important factor that is gaining increasing attention is performance of the ski boots, which act as an interface between the physical performance of the skier and the performance of the skis. Top-level skiers prefer ski boots with a tight fit that are custom-made by heat-molding the shell or shaving the shell inside to fit the shape of the foot. These modifications are made to minimize the time lag between the skier's movement and movement of the skis. Most ski boots for top-level skiers are also designed now with adjustments made for the center line of the foot in the ski boot in relation to the center line of the ski so that energy can be transmitted efficiently from the skier to the skis during turns. Speed in alpine ski competitions is becoming faster every year due to improvements in skis, boots and wax, and research and development of ski equipment based on engineering concepts is needed to further enhance performance and guarantee of safety of skiers.

Most previous studies on alpine ski racing have focused on the mechanical properties and design of skis[(1)-(5)] and on the basic relationship between turning movements and ski design[(6)-(13)]. Although results of a study on turning techniques based on analysis of skier's

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Table 1 Body segmental proportions for Japanese and Westerners

Body segment	Proportion	
	Japanese	Westerner
Head	0.140	0.130
Trunk	0.300	0.288
Thigh	0.230	0.245
Shank	0.276	0.285
Foot	0.148	0.152

(Japanese data: published by Ae, Westerner data: published by Winter)

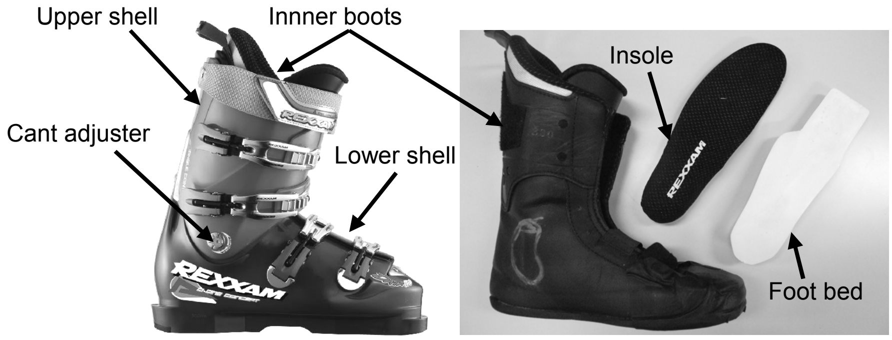


Fig. 1 General components of a ski boot

movements with the aim of enhancing performance of the skier have been reported[20], there has been no study on the relationship between the skier's skeletal frame and ski boot design. This study was therefore carried out to experimentally analyze the ski boot design based on leg frame with the aim of enhancing performance of the alpine skier. It was shown in this study that upper shell design based on shank length is important for enhancing performance, and the effectiveness of the new design was verified in laboratory experiments and in slalom and giant slalom tests.

2. Ski boot design and competition results

2.1 Body segmental proportions and shell design

General components of a ski boot are shown in Fig. 1. A ski boot has a cant adjuster for an individual shank inclination of skiers at a joint between the upper and lower shells. However, the basic shell design cannot be changed for each of skiers. If two skiers with different skeletal frames ski with identically designed boots, it is possible that they cannot perform the same movements due to differences in body segmental proportions and inertia characteristics. During fast turns in competition, skiers must maintain balance and center position. Since ankle joint movements are important for maintaining balance[14], the ratio of shank length to total shell height, which affects ankle joint movement, should be an important factor. We therefore investigated the effects of differences in body segmental proportions and inertia characteristics on maintenance of balance and center of mass. As a favorable example for the investigation of the physical differences, body segmental proportions of Westerners and Japanese based on statistics published by Winter[15] and Ae et al.[16], respectively. A comparison of the ratios of body part lengths to total body height for Japanese and Westerners is shown in Table 1. Body segments are separated at the vertex, upper border of the sternum, site of the greater trochanter, center of the knee joint and center of the ankle joint. For Japanese and Westerners of the same height, Japanese generally have longer trunks and shorter thigh or shank length than those of Westerners, but

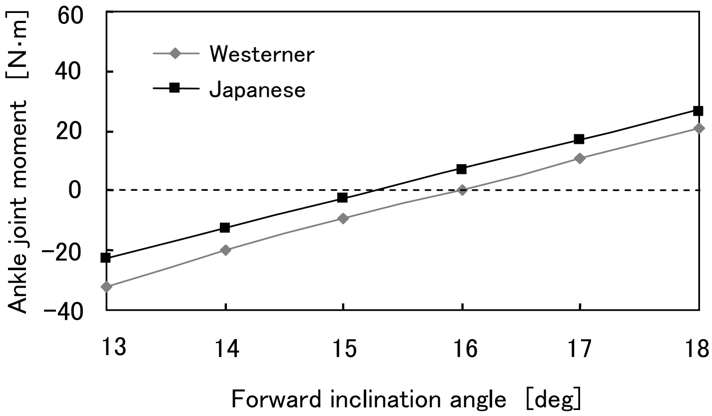


Fig. 2 Center positions of Japanese and Westerners

foot size is not greatly different and it is therefore likely that they will use ski boots with the same shell size. In the crossover in the turn transition phase, the center of gravity is shifted greatly in the direction of the fall line. It is easy to imagine that this shift in center of gravity during the crossover will become difficult if the boot shell is too high in relation to shank length because shank movement will be restricted when the ankle joints are moved in the crossover maneuver. Calculations showed that shell height for Japanese skiers should be 3.2% smaller to make the ratio of shank length to shell height the same as that for Westerners.

Next, the center body positions of Japanese and Westerners were calculated by using a simplified rigid body model based on the body segmental proportion. In this calculation, it was assumed that the position in which the sum of the moments around the ankle joint due to effects of gravity and inertia acting on various parts of the body was zero was the center position. This is considered to be the position in which muscle work to maintain balance is minimized and energy can be transmitted to the skis with most efficient utilization of the action of the center of gravity. Assuming that the forward inclination angles of the shanks and the trunk are the same in the static center position, the relationship between forward inclination angle and calculated moments at the ankle joints arising from body mass distribution is shown in Fig. 2. A comparison of the center positions of Japanese and Westerners shows that the forward inclination angle at which moments at the ankle joints become zero is smaller for Japanese, indicating that Japanese skiers must have a slightly more upright position in order to efficiently transmit energy to the skis.

The above results show that shifting the center of gravity in the direction of the fall line during crossover will be difficult for a skier with smaller shank length who is wearing the same boots as those worn by a skier with larger shank length due to difficulty in maintaining balance. Moreover, a skier with smaller shank length will assume a more upright position in order to maintain the center position during a turn. Thus, in order for the skier to be able to maintain balance and center position when skiing, the height of the boot shell and the forward inclination angle of the shank must be matched to the skier's shank length. The forward inclination angle of the shank when wearing ski boots is affected not only by the forward inclination of the shell but also by the total shell height and by the shape of the foot bed or insole. This study focused on the appropriate design of the upper shell for shank length.

2.2 Finish time and lean angle

Alpine ski racing is a sport in which the time it takes a skier to ski down a designated course from a starting gate to finishing gate is recorded. The time depends not only on the level of physical strength of the skier but also on skiing technique and course strategy. There have been various studies on course strategy, including a study on the fastest route[17],

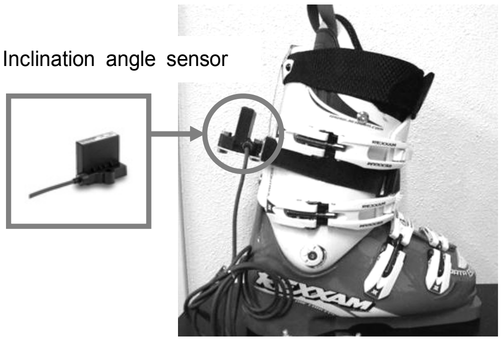


Fig. 3 Measurement of maximum lean angle using an inclination angle sensor

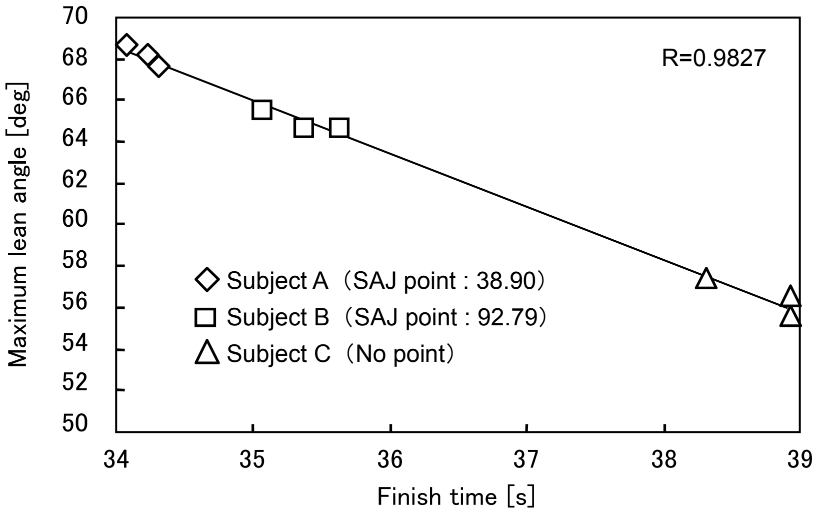


Fig. 4 Relationship between finish time and maximum lean angle

but it is generally considered that shortening turning time and extending gliding time in order to maximize acceleration down the fall line are effective techniques(18). As long as the radius of curvature determined by the side curve of the ski remains regulated by international rules, minimizing the effective radius of curvature by assuming a large lean angle when turning is considered to be important for shortening turning time(11). Here leaning is defined as increasing the roll angle of the skis by leaning the legs inward in the turn arc. First, in order to clarify the effect of lean angle on finish time, the relationship between finish time and maximum lean angle was investigated by attaching lean angle sensors (OMRON Linear Lean Angle Sensor D5R-L02-60) to the rear sides of the upper shells of ski boots as shown in Fig. 3 and measuring lean angles of skiers of different skill levels (subjects A, B and C) when skiing down the same giant slalom course. The skill levels of the subjects were determined by SAJ (Ski Association of Japan) points. Subjects A and B had SAJ points of 38.90 and 92.79, respectively, and subject C had no SAJ points. Therefore, subjects A and C were judged as having the highest and lowest skill levels, respectively. Measurements of time and maximum lean angle were performed three times for each subject, and were compared in Fig. 4. As can be seen in the figure, maximum lean angle increased in inverse proportion to the finish time with increase in skill level, and a correlation coefficient R was nearly equal to 1. Consequently, it was demonstrated that the lean angle became larger if the skill level of a ski racer was higher in order to shorten the finish time.

Advanced skiers generally reduce the lean angle to prepare for crossover in the latter

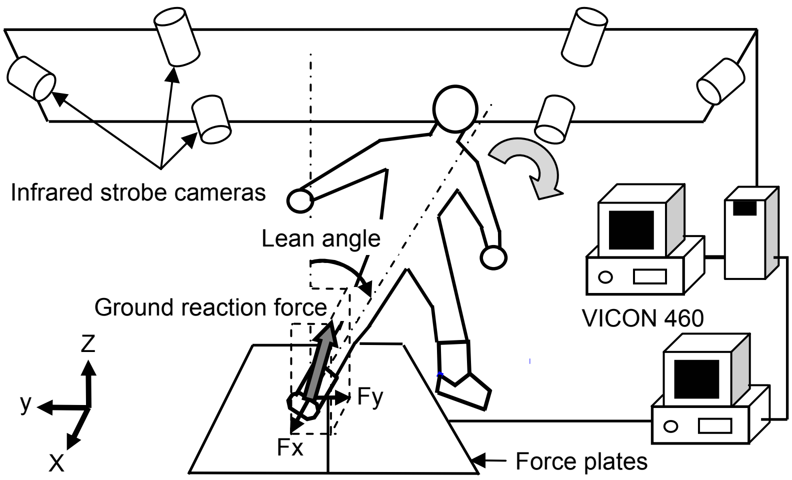


Fig. 5 Experimental apparatus for measuring of leaning balance

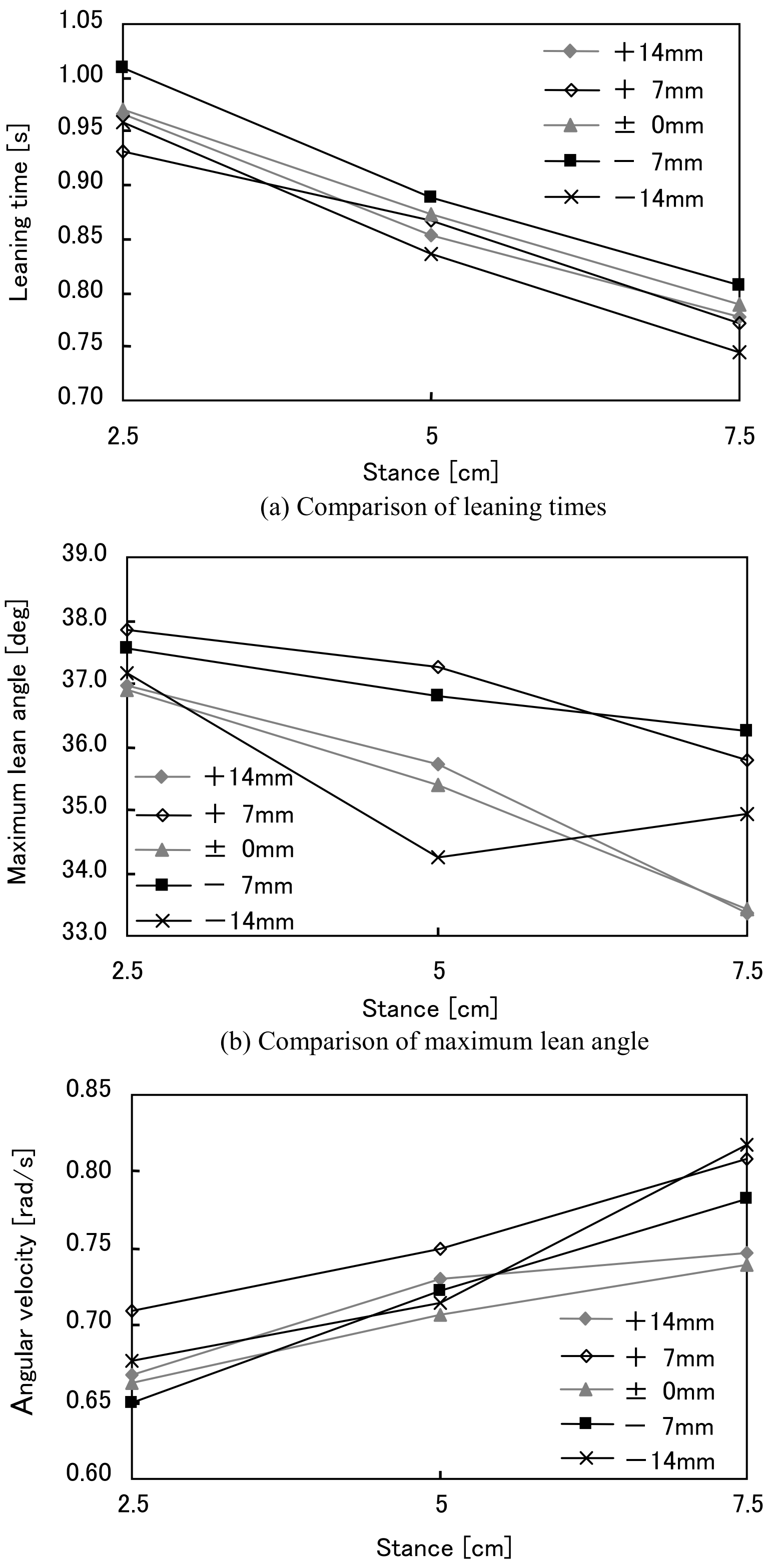
half of the turn(19). Thus, body movement to increase the lean angle is performed mainly in the first half of the turn, and skiers must therefore lean inward at a large angle in as short a time as possible after crossover in order to improve time. In this study, an upper shell that enables balance to be maintained easily and enables a large lean angle to be achieved quickly was designed with the objective of improving time for alpine skiers.

3. Laboratory experiment on balance when leaning

3.1 Experimental apparatus and methods

In order to investigate the design of the upper shell in detail, movements when a subject wearing ski boots was leaning inward while standing on one leg were analyzed. As shown in Fig. 5, angular velocity of the shank when leaning and maximum lean angle were measured using a 3-dimensional motion capture system, VICON460, and change in ground reaction force when leaning was measured by using Kyowa Dengyo force plates.

After marking standing position on the force plate, the subject stood on the plate bearing weight evenly on both feet and then the subject raised one leg off the plate to intentionally disturb initial balance and leaned inward as much as possible while standing on one leg. The center points of the knee and ankle joints were determined from infrared reflecting markers attached to the leg the subject and to the ski boot, and the lean angle and mean angular velocity when leaning were calculated from a vector joining the center points of the knee and ankle joints. Since the leaning motion would differ greatly if the subject shifted his center of mass to the supporting leg when standing on one leg, ground reaction force was monitored to ensure that there was no shift in center of mass when starting to lean. Maximum lean angle is the lean angle when the subject could lean no further. Since the ground reaction force suddenly becomes smaller at the limit of leaning by start of the slip of a supporting leg, maximum lean angle was determined by the change in ground reaction force. The ski boots used in the experiment were all REXXAM DATA130R boots (Ryusho Industries). Five types of boots, including normal boots with no modification to the upper shell and boots with modifications of ±7.0 mm and ±14.0 mm in upper shell height, were used. Three standing positions were used: 25 mm, 50 mm, and 75 mm from the center point between the feet in the standing position to the inner side of the lower shell sole of each boot. The subject was 165 cm in height and 62 kg in weight and was a healthy adult alpine skier with SAJ GS points of 144.44. Measurements were performed ten times in each standing position, and the mean values were compared.



(a) Comparison of leaning times

(b) Comparison of maximum lean angle

(c) Comparison of angular velocity

Fig. 6 Differences in leaning movements depending on upper shell design

3.2 Results of the experiment

Measurements of leaning time, maximum lean angle and angular velocity are shown in Figs. 6(a), (b) and (c), respectively. Longer leaning time was made possible by the upper shell design that enables easy maintenance of balance. The results presented in Fig. 6(a) indicate that maintenance of balance was easiest in the case of boots with a 7.0 mm lower upper shell. Seven millimeters is 3% of the total shell height (232 mm), and the results presented in Fig. 6(a) therefore support the results of analysis of body segmental proportions described in the previous section. On the other hand, as shown in Figs. 6(b) and (c), the values of maximum lean angle and angular velocity, which are important factors for improving time, were both high in the case of boots with 7.0 mm higher upper shell. Thus, these results indicate that reduction in upper shell height in accordance with body segmental proportions improves maintenance of balance but makes quick leaning at a large angle impossible. Ground reaction forces were compared to determine the reason for this. Figure 7 shows an example of the experimental results of the ground reaction force component in the anteroposterior direction of the subject (Fx) and the ground reaction force component in the mediolateral direction of the subject (Fy). The horizontal axis represents the normalized time from the start to completion of leaning. Fx changes with plantar flexion and dorsiflexion of the ankle joint, and Fy changes with pronation and supination of the ankle joint. If balance is optimally maintained in the center position when leaning, Fx becomes zero and smoothly increases or decreases depending on the direction of leaning. Fx in the case of the -7.0 mm shell height showed slight variations above and below zero, indicating that the ankle joint was functioning correctly for maintenance of balance, whereas Fx in the case of the +7.0 mm shell height showed only one large variation, indicating that the ankle joint was not functioning correctly for maintenance of balance. These results indicate that adjustment of the center of mass by plantar flexion and dorsiflexion movements of the ankle joint when wearing a ski boot greatly affects the maintenance of balance. Fy in the case of the +7.0 mm shell height showed smooth variation from the start to completion of the leaning movement, whereas Fy in the case of the -7.0 mm shell height showed an abrupt change near the completion of the leaning movement when the lean angle approaches the maximum angle. This indicates that balance adjustment by pronation and supination of the ankle joint is important when the lean angle large and suggests that fine adjustment cannot be made in the case of insufficient shell height because the body is supported by the lateral part of the upper shell in contact with the lateral aspect of the shank when the lean angle becomes large.

The results of this experiment indicate that balance in the anteroposterior direction can be maintained easily and maintenance of center position is easy if upper shell height is reduced, whereas balance in the mediolateral direction is easier and maximum lean angle and angular velocity become greater in the case of larger upper shell height. This means that a lower shell would be effective in crossover at the turn transition phase, when maintenance

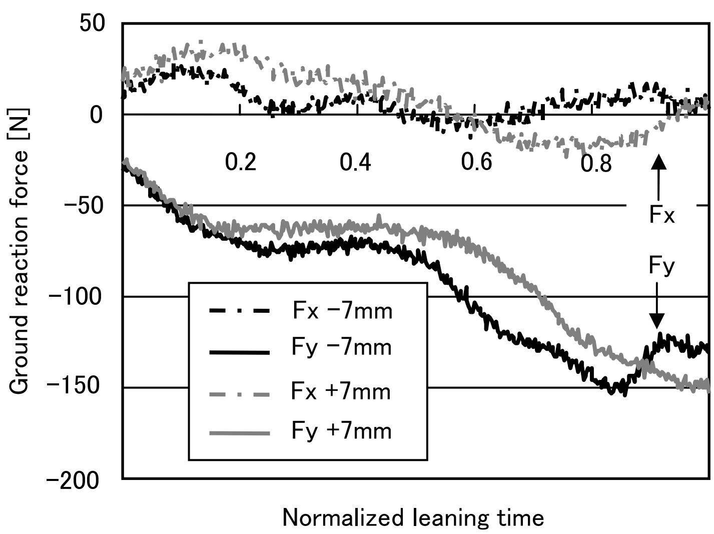


Fig. 7 Comparison of changes in ground reaction forces when leaning

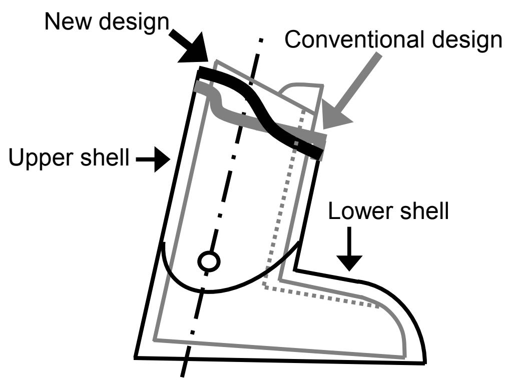


Fig. 8 New design of an upper shell based on leg frame

Table 2 Design of an upper shell

Test boots	Upper shell modification	
	Front	Rear
Type 1	-7 mm	-7 mm
Type 2	±0 mm	+7 mm
Type 3	-7 mm	+7 mm

(±0: Normal shell)

of balance is important, whereas a higher shell would be effective when the lean angle in the turn approaches the maximum value. If center position is maintained when skiing, the front part of the upper shell mainly comes into contact with the shank at the turn transition phase and the lateral to posterior part of the upper shell comes into contact with the shank during the turn. Since the same tendency appeared in all measurements of the change of the ground reaction force, it might be possible to enhance performance in both phases of the turn by reducing the height of the upper shell at the front and making the shell height gradually higher from the side to back as shown in Fig. 8.

3.3 Tests of shell designs

Tests on balance when leaning were conducted using ski boots with three different height designs of the front part and side to back part of the upper shell in order to determine the effectiveness of the upper shell design described above. Upper shell heights tested are shown in Table 2, and results for maximum lean angle and rate of change in lean angle for each design are shown in Fig. 9. As expected, the largest values of both maximum lean angle and angular velocity were observed in the case of the upper shell design with reduced height in the front and increased height from the side to back (Type 3). Leaning time was longest with Type 1, but the difference between leaning times for Type 1 and Type 3 was only 0.03 s (about 3% of leaning time), indicating that Type 3 design was sufficient for maintenance of balance.

3.4 Optimal design

It was experimentally shown that Type 3 boot design might be effective for shortening finish time in an alpine ski race. However, there is no guarantee that an upper shell design with 7 mm reduction in height of the front part and 7 mm increase in height of the rear part is effective for all skiers with different frames and different levels of skill. Leaning balance experiments were therefore carried out in the laboratory in which subjects with different frames and different levels of skill wore Type 3 prototype boots, their own boots and normal DATA130R boots.

The relationships of the ratio of front and rear heights of the upper shell, based on the

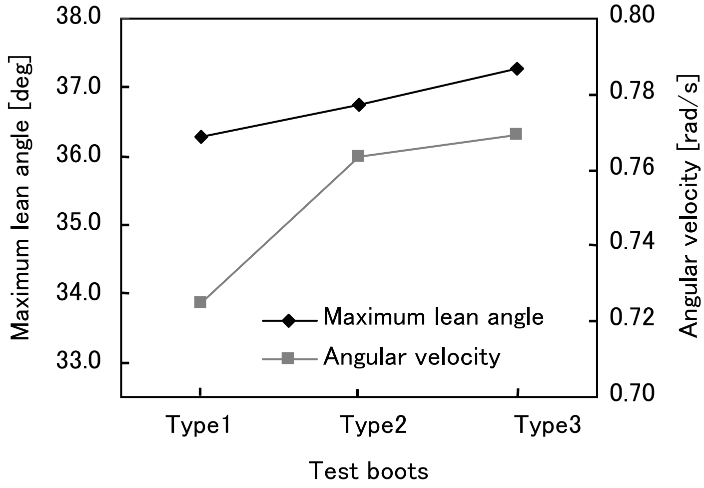
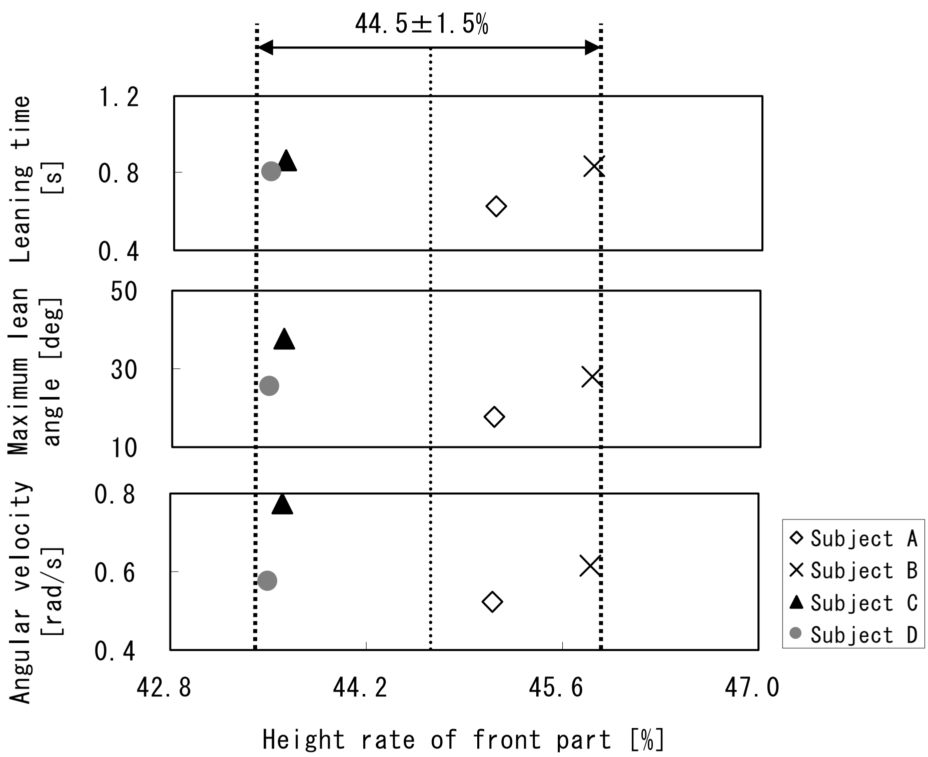
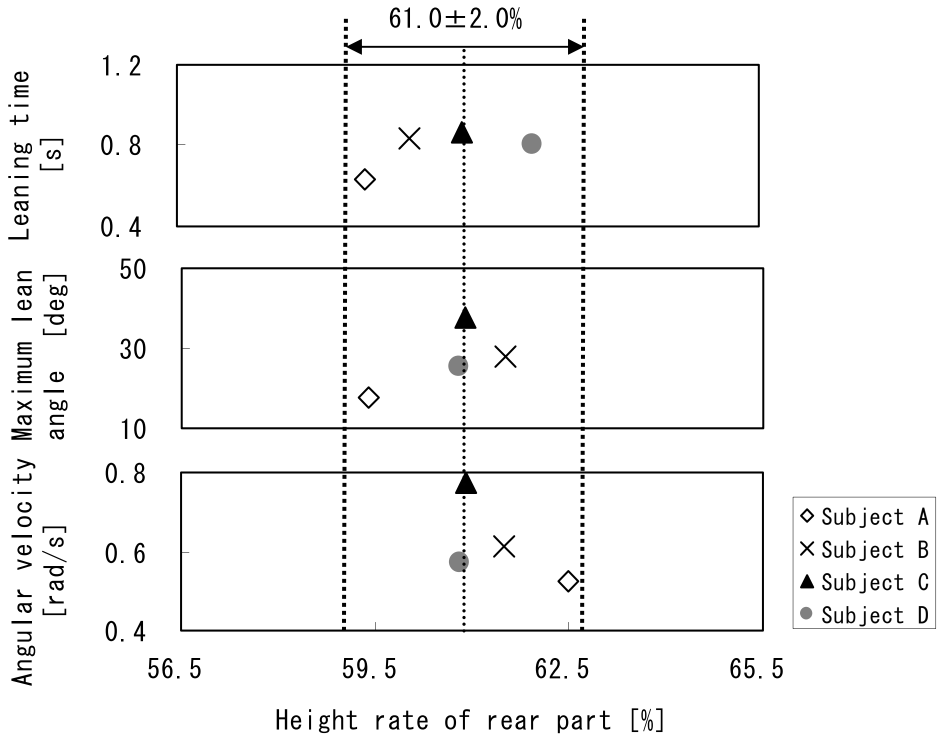


Fig. 9 Tests on effectiveness of upper shell design

height from the bottom of the ski boot to the upper border of the patella with the subjects wearing the boots, with leaning time, maximum lean angle and angular velocity were investigated. Four subjects with different levels of skill participated in the experiment. Three subjects had SAJ GS points of 20.82, 106.53 and 144.44, and the other subject had no points. Measurements were carried out five times for each boot type and the values were averaged. The relationships of maximum values of leaning time, maximum lean angle and angular velocity with upper shell height ratio are shown in Figs. 10(a) and (b). Lean time, maximum lean angle and angular velocity all showed the highest values regardless of skill level in the case of upper shell design in which heights of the front part and back part were 44.5±1.5% and 61.5±2.0% of the height of the upper border of the patella, respectively. The results therefore indicated that the upper shell can be optimally designed for each skier based on the height of the upper border of the patella.



(a) Optimum design of a front part of the upper shell



(b) Optimum design of a rear part of the upper shell

Fig. 10 Optimal values of upper shell design

4. Field tests

Tests were carried out at a ski field to determine whether the new upper shell design is actually effective for enhancing performance. First, a skier (D.S.) belonging to the All Japan Male Junior Team (SAJ GS points: 12.00, FIS GS points: 38.73, SAJ SL points: 7.43, FIS SL points: 31.36, FIS: International Ski Federation) who usually used DATA130R boots participated in giant slalom and slalom time trials. The Type 3 prototype boots were used without adjustments because the upper shell heights were optimal for the subject. As shown in Table 3, despite the fact that the course was short, the times when wearing the newly designed boots were 0.10 to 0.44 seconds shorter than the times when wearing normal DATA130R boots. These are large time differences for alpine ski racing, confirming that the Type 3 design is effective for top-level Japanese skiers.

To further investigate the effectiveness of the upper shell design, maximum lean angle and time were recorded for an alpine skier of medium skill level (SAJ GS points: 131.32) wearing the Type 3 design boots. As shown in Fig. 11, inclination angle sensors were attached to the ski boots to record lean angle, and the data logger and electricity amplifier were placed in a waist pouch so that they would not make contact with the poles. The subject skied down a giant slalom course and the time was recorded using BROWER timing system. Maximum lean angle and time were recorded for three types of boots: boots the subject normally used, normal DATA130R boots and boots with the newly designed upper shell. The upper shell height was adjusted at the front and back to 45.0% and 62.5% of the patella height of the subject, respectively. Measurements were carried out three times for each type of boot, and maximum lean angles and times were averaged. As shown in Fig. 12, maximum lean angle increased and time was shortened when the subject wore the boots with upper shell height optimally adjusted to patella height. The results therefore showed that boots with optimal adjustment to upper shell height determined in laboratory experiment enhance performance of the skier.

Table 3 Comparison of times for an All Japan Junior Team skier

Event	Trial number	Boots	Finish time [s]
Giant Slalom	1	Normal	25.74
	2	Normal	25.45
	3	Type 3	25.35
	4	Type 3	25.30
Slalom	1	Normal	29.53
	2	Normal	29.53
	3	Type 3	DF
	4	Type 3	29.27

(DF : Did not finish)

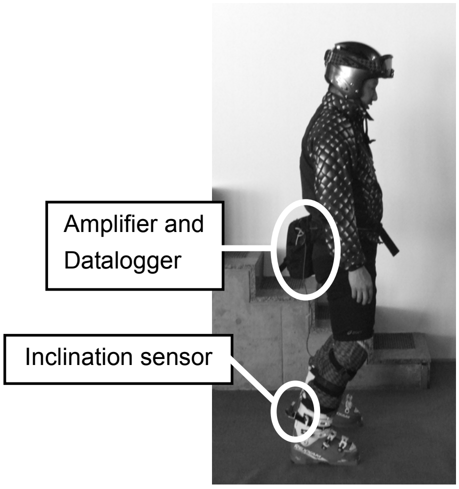


Fig. 11 Subject for recording the lean angle and the finish time in giant slalom test

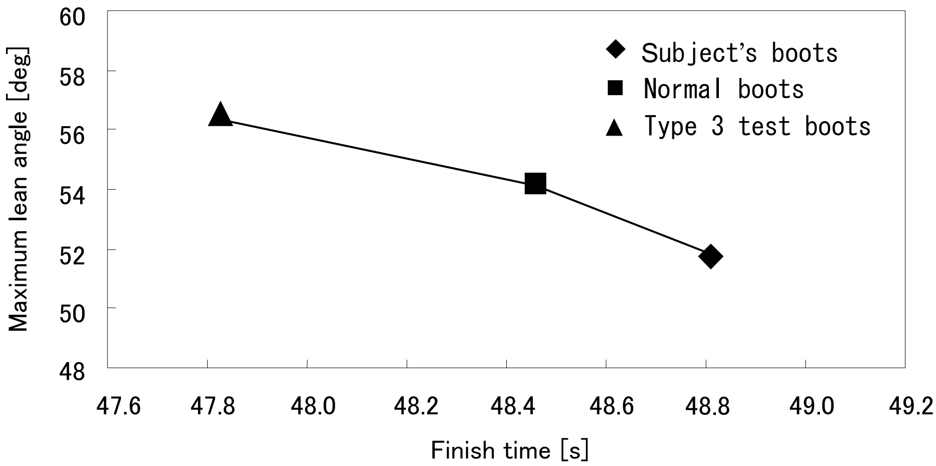


Fig. 12 Tests on the effectiveness of the optimally designed upper shell in giant slalom trials

6. Conclusions

A new ski boot design aimed at enhancing the performance of alpine skiers was experimentally investigated with consideration given to differences in skeletal frames of skiers. Results of experiments on optimal upper shell design carried out in the laboratory showed that finish time, maximum lean angle and angular velocity could all be improved regardless of skill level by wearing boots with upper shell design in which heights of the front part and back part were 44.5±1.5% and 61.5±2.0% of the height of the upper border of the patella, respectively. The effectiveness of this design was also investigated in tests conducted on giant slalom and slalom courses by a top-level skier in Japan and a skier with a medium level of skill. The results showed that lean angle during turns was increased and finish time was shortened when the skiers wore the newly designed boots. Further studies are planned to investigate the effects of foot bed design and shell forward inclination angle.

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