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Changes in the Lower Limb Joint Angle during the Simulated Skiing

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Abstract. [Purpose] This study conducted a 3-dimensional kinematic analysis in order to examine changes in the movements of the lower limb joints during simulated skiing, to prevent skiing-related injuries. [Subjects] The participants (8 males, average age: 30.3 ± 3.0 years, average height: 178.5 ± 3.9 cm, average weight: 79.9 ± 3.4 kg, average career: 7.5 ± 1.9 years) held a certificate issued by the Korea Ski Instructors Association. [Methods] This experiment was conducted using a motion analysis system which recorded the subjects training on a ski simulator. The hip, knee and ankle joints' ranges of angles were measured in the sagittal and coronal planes during simulated skiing. The paired t-test was conducted in order to examine changes in the lower limb joint motions. [Results] After training on the ski simulator, the range of angles of the performers' hip joints in the sagittal plane decreased in each of the analyzed events. The range of angles of the knee joints in both the sagittal and coronal planes increased. Movements of the ankle joints in the sagittal plane, and overall movements of the left and right sides decreased. [Conclusion] To avoid skiing injuries in the lower limbs, exercise to strengthen the quadriceps and hamstring muscles to balance their strength is necessary. In particular, exercise to strengthen the hamstring muscles is required
Key words: Lower limb, Simulated skiing, 3-Dimensional kinematic analysis

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INTRODUCTION

Skiing is a sport that requires precise adjustment of and complex interaction between the upper and lower body muscles, and it is also a rotational exercise in which a skier descends while continuously making turns from the start to the end point[1)]. In skiing, the force that enables rotation is centripetal force. This force is generated by the motion that a skier deploys at the internal center of rotation and that occurs when the skier tilts his or her body in order to set an edge angle. Turning force is created by properly employing centripetal force[2)]. Furthermore, despite external forces, such as the frictional force of the snow surface and gravity, and the skier's lower body load, rapid and stable turns need to made[1)]. Therefore, skiing requires a lot of muscle strength in the lower limbs, and the knee joint and ankle joint muscles act as protagonists in turning and edging techniques, respectively[3)]. Skiing is a closed kinetic chain exercise because the feet are fixed in the boots. During a closed kinetic chain exercise, the lower limbs are protected by the articular capsule and all parts of the lower limbs move simultaneously. A force that applies to a part of the kinetic chain needs to be absorbed by the open part of the chain, as well as by other parts of the chain. However, when the force is too big, damage occurs[4)]. Since strong muscle strength in the lower limbs is required, skiing and damage to the lower limbs are inseparably linked. Among injuries incurred while skiing, 55% are lower limb injuries, the majority of which involve the knee areas, including ligaments[5)]. Among ligament injuries, anterior cruciate ligament (ACL) injuries typically occur in high-speed downhill skiing during the landing phase following a jump[6)]. In many ways, including its kinematic characteristics, skiing is one of the best winter sports. However, due to exposure to a high-speed environment without protective equipment, it is a sport in which the frequency or severity of resulting injuries surpasses a variety of other sports. In addition to an increase in the skiing population, the rapid increase in the absolute number of injuries incurred while skiing has made the sport a major issue of interest in the area of sport injuries[5)]. At a time when Korea is preparing to host the Winter Olympic Games, interest in skiing is growing. Surprisingly, however, in the area of sports physical therapy, interest in skiing injuries is very low. Accordingly, this study analyzed changes in joint angles of the lower limbs using a ski simulator to provide basic data for use in the prevention of skiing-related injuries.

SUBJECTS AND METHODS

Participants in this study's experiment were 8 male adults (average age: 30.3 ± 3.0, average height: 178.5 ± 3.9 cm, average weight: 79.9 ± 3.4 kg, average number of career years: 7.5 ± 1.9 years) who lived in the B area, and had similar physical conditions with no physical disabilities. All the subjects held a certificate issued by the Korea Ski Instructors Association, and knew how to use a ski simulator. This experiment was conducted after its purpose and method were sufficiently explained to the participants and they had consented to participate in this experiment. This experiment was conducted at a motion analysis laboratory in B Hospital located in B City. A total of 20 sessions of training on the ski simulator were performed, with each training session lasting for 1 minute and followed by rest for 1 minute[7]. The first round of measurements was made after the first training session and the second round of measurements was made after all 20 sessions of training. The ski simulator (Skier's edge, UK) presents not the reality of skiing itself, but rather is equipment that embodies a situation similar to that reality. It helps performers reproduce the sense of exercise necessary in skiing within a limited environment and space—not on the slope. The ski simulator was fixed on a flat surface. The task was executed on the ski simulator, which consists of a platform on wheels that moves left and right on two bowed, parallel metal rails. Rubber belts fasten the platform to the rails and ensured that it regains its resting position in the middle of the apparatus[8]. The subjects did stretching and warm-up exercises for 10 minutes and then performed the ski training sessions. They wore tight pants in order to reduce discomfort and errors while collecting data, and they held a pole in each hand. No special control was applied to the hands holding the poles. The ski-simulator's band elasticity had a rotation radius of 1 to 10 levels; the larger the rotation radius was, the weaker the band elasticity was. This study conducted the experiment with three levels of elasticity strength[7]. There was no restriction on the number of performances of ski simulations, and participants were allowed to repeat the simulations in a good posture as many times as possible. A total of 8 infrared cameras were used to record the participants' performance of ski simulations and motion data were sampled at 200 Hz. Then, in order to set the reference frame, a calibration was conducted using an L-shaped frame and surface markers were placed on 18 areas of the lower limbs to obtain the location coordinates of segments and joints (Table 1). For the analysis of motions on the ski simulator, the points in time when the participants were at the center, when they were at the right peak, when they were at the center again, when they were at the left peak, and then when they were at the center again were defined as Event 1, Event 2, Event 3, Event 4, and Event 5, respectively. The hip, knee and ankle joints' sagittal and coronal movements were analyzed. To calculate the values of the kinematic variants, 3-dimensional coordinate values, obtained using Vicon's motion capture system, were analyzed with Nexus Polygon (Vicon Motion System, Ltd., UK) and Excel 2007 (Microsoft Inc., USA). Samples of the first and the last sessions of the 20 sessions of simulated skiing were used as data, and one continuous motion from the left to the right side judged to be the most appropriate in each session was selected as a sample.

Data of the participants' performance were collected using Vicon's Nexus software program and statistically processed using SPSS Version 12.0. The paired t-test was conducted in order to examine changes in the lower limb joint motions between the first and last performance of ski simulation, and differences were considered statistically significant at a p-value of less than 0.05.

Table 1. Reflective markers

No.	Area	No.	Area	No.	Area
1	LFWT	7	LSHN	13	LTOE
2	RFWT	8	RSHN	14	RTOE
3	LTHI	9	LANK	15	LBWT
4	RTHI	10	RANK	16	RBWT
5	LKNE	11	LMT5	17	LHEE
6	RKNE	12	RMT5	18	RHEE

1) left front waist 2) right front waist 3) outside middle of left thigh 4) outside middle of right thigh 5) outside of left knee 6) outside of right knee 7) left shin 8) right shin 9) left ankle 10) right ankle 11) outside of left foot where toes start 12) outside of right foot where toes start 13) left foot just before big toe starts 14) right foot just before big toe starts 15) left back waist 16) right back waist 17) left heel 18) right heel.

RESULTS

The results of the analysis of the lower limbs' joints range of angles changes at the end of simulated skiing are as follows. For the hip joints' movements in the sagittal plane (flexion and extension), the range of angles of the left ($p<0.01$) and right sides ($p<0.001$) decreased with statistical significance in Event 1 at the end of simulated skiing. In Event 2 as well, both sides decreased with statistical significance ($p<0.01$). In Event 3, the left side ($p<0.01$) decreased significantly, and in Events 4 and 5 both the left and right sides of the hip joints range of angles decreased. In most events, the range of angles of the left and right sides' movements in the sagittal plane decreased. Regarding the hip joints' movements in the coronal plane (adduction and abduction), in Event 1, the left side decreased ($p<0.001$) and the right side increased ($p<0.05$). In Event 4, the range of angles of the right side of the hip joints increased significantly ($p<0.05$).

For the knee joints' movements in the sagittal plane (flexion and extension), the range of angles of the left side increased with statistical significance ($p<0.05$) and that of the right side increased as well, but without statistical significance, in Event 1. In Event 4, the right side's range of angles increased ($p<0.05$), and in Events 3 and 5 as well, the right side's range of angles significantly increased. For the knee joints' movements in the coronal plane (flexion and extension), the range of angles of the right side ($p<0.01$) increased with statistical significance ($p<0.01$) in Event 1. The range of angles of the left side ($p<0.05$) in Events 2 and 3 and that of the right side in Event 4 increased with statistical significance ($p<0.01$). In Event 5, the range of angles of both sides increased with statistical significance ($p<0.05$). In summary, in all events except for Event 2, both sides increased after the 20 sessions; in Event 2, only the left side increased.

For changes in the ankle joints' movements in the sagittal plane (dorsal and plantarflexion), the angle of the left side

Table 2. The change of hip, knee and ankle joint angles

			E1		E2		E3		E4		E5	
			L	R	L	R	L	R	L	R	L	R
Hip	Fle/Ext	pre	44.2 ± 3.3	34.9 ± 3.2	44.4 ± 7.0	22.3 ± 7.1	38.0 ± 1.9	34.5 ± 5.1	25.5 ± 6.0	39.6 ± 7.0	40.3 ± 3.8	36.6 ± 3.2
		post	37.2 ± 3.8	29.9 ± 2.6	41.9 ± 7.5	20.4 ± 7.9	31.6 ± 5.5	32.6 ± 5.4	19.5 ± 8.1	36.5 ± 9.4	36.2 ± 4.3	32.6 ± 3.5
	Add/Abd	pre	5.1 ± 5.7	-2.9 ± 7.0	6.3 ± 5.4	13.1 ± 7.7	0.7 ± 5.5	6.8 ± 5.7	14.4 ± 3.6	11.8 ± 2.0	8.3 ± 3.4	1.8 ± 3.7
		post	10.1 ± 4.3	1.7 ± 7.7	4.4 ± 8.6	13.8 ± 8.7	1.7 ± 9.2	7.1 ± 8.3	15.8 ± 7.0	15.4 ± 4.8	10.0 ± 4.3	4.0 ± 8.3
Knee	Fle/Ext	pre	44.5 ± 3.0	33.7 ± 1.6	58.6 ± 7.3	26.6 ± 5.2	39.7 ± 6.0	34.4 ± 4.5	28.8 ± 7.9	53.0 ± 9.8	39.3 ± 3.0	33.7 ± 5.6
		post	53.6 ± 8.0	39.3 ± 7.7	61.5 ± 3.5	29.3 ± 10.7	39.0 ± 5.0	41.5 ± 7.7	28.9 ± 5.1	60.8 ± 13.1	44.2 ± 3.9	39.5 ± 5.6
	Val/Var	pre	9.8 ± 5.4	12.4 ± 4.1	17.6 ± 6.5	5.2 ± 3.3	7.2 ± 4.3	11.7 ± 5.4	1.9 ± 4.7	23.1 ± 7.0	3.9 ± 6.8	14.1 ± 3.5
		post	11.7 ± 2.4	16.0 ± 2.5	22.5 ± 11.6	4.6 ± 3.2	11.3 ± 1.5	12.6 ± 4.0	2.4 ± 4.7	26.7 ± 5.2	9.0 ± 6.1	16.5 ± 1.9
Ankle	Dor/Pla	pre	31.1 ± 4.9	28.5 ± 7.8	31.8 ± 2.5	24.0 ± 2.8	27.7 ± 1.2	28.2 ± 5.4	28.3 ± 5.0	37.4 ± 2.8	29.4 ± 4.1	28.4 ± 5.7
		post	25.3 ± 3.5	24.1 ± 1.0	28.6 ± 4.6	24.8 ± 5.2	24.3 ± 3.3	26.0 ± 4.2	24.2 ± 3.0	34.4 ± 5.0	23.7 ± 5.2	24.2 ± 1.8
	Inv/Eve	pre	1.9 ± 0.8	2.1 ± 1.0	1.2 ± 0.2	2.9 ± 1.3	0.0 ± 1.3	3.8 ± 2.4	1.4 ± 1.2	4.3 ± 2.6	1.3 ± 1.5	2.7 ± 1.7
		post	1.8 ± 1.0	3.0 ± 2.5	0.2 ± 0.1	3.8 ± 0.5	0.1 ± 1.5	3.5 ± 1.1	1.6 ± 1.0	4.7 ± 1.2	1.9 ± 1.5	3.1 ± 1.7

*$p<0.05$, **$p<0.01$, ***$p<0.001$

in Event 1 significantly decreased ($p<0.001$). In Event 4 as well, the range of angles of the left side decreased ($p<0.01$), and in Event 5 the range of angles of both sides decreased significantly ($p<0.001$). Overall, in most events, the range of angles of both sides decreased with statistical significance. Regarding the ankle joints' movements in the coronal plane (inversion and eversion), the left side decreased significantly in Event 2 ($p<0.001$), and increased significantly ($p<0.01$) in Event 5.

DISCUSSION

This study conducted a 3-dimensional kinematic analysis in order to examine changes in the movements of the lower limb joints during simulated skiing, to provide basic data for the prevention of skiing-related injuries.

After performing skiing motions on a ski-simulator, the range of angles of the performers' hip joints on the sagittal plane decreased in each analyzed event, increasing the range of flexion of the hip joints. We consider this result arises from a decrease in exercise ability caused by fatigue with the passage of time. With respect to movements in the coronal plane, the range of angles of the joints after the performance of simulated skiing increased in Event 1, with an increase in the inclination angle. This result is similar to that reported by Nourrit D, Delignieres D, et al.[8], who found that expert skiers not only created inclination angles by bending their bodies, but also created deep angles by gradually moving their center of gravity away from their skis and the expert skiers showed large flexion angles of the hip joints. In this study, after the performance of skiing motions on the ski-simulator, the angle of the knee joints in the sagittal plane increased in each categorized events. This result is similar to that of another study[10], which found that expert skiers stretch their knee joints as much as possible and use extension muscles. In Events 1, 3, and 5, when the participants were at the center of the ski simulator, the range of angles of their knee joints were 60 degrees or lower, and in Events 2 and 4, when the participants were positioned at either the left or right sides, they were around 60 degrees. The knees' extension muscles exert maximum strength at around 60 degrees, and flexion muscles at between 10 and 45 degrees. Quadriceps femoris and hamstring muscles are important for a sense of balance at the early and final stages of turns. In particular, hamstring muscles play an important role in protecting the knees and preventing injuries[11]. According to Kim, expert skiers' quadriceps femoris muscles are strong, while their hamstring muscles are relatively weak and such imbalance is likely to result in injuries[10]. Regarding the knee joints' movements in the coronal plane, angles generally increased with increased inclination. In particular, in Event 2 (at the right-side peak), the angle of the left knee joints increased, and that of the right knee joints increased in Event 4 (at the left-side peak), suggesting that the knee joints create inclination angles in the direction in which the skier tries to turn. With regard to movements of the ankle joints in the sagittal plane, in most of the analyzed events, overall movements of the left and right sides decreased. When the ankles' range of motion (ROM) decreases, it affects other joints in order to compensate for the restriction of the ankle ROM[12], resulting in too much stress on the knee joints. In particular, this condition may be predominant in a closed kinetic chain exercise for the lower limbs like skiing. In actual skiing, the boots protect the ankle areas, leading to injuries in other areas, namely the knees, to compensate for the restriction of the ankle joints' ROM. Regarding movements of the ankle joints in the coronal plane, the angle of the left side increased in Event 2 (at the right-side peak). These are necessary motions for bending the body and turning skis. Skiers need to push their skis as far as possible from their bodies' center of gravity and at the same time maintain the inclinations of the left and right ankle joints parallel to each other. In order to regain balance, recovery is made by a forceful contraction of the quadriceps muscles. It is during this recovery movement, as skiers themselves have reported, that their ACLs are at risk. If the joints' ROM is large and the body's center of gravity moves well, manipulation of skis is easy and stable turns may be performed[5].

As suggested by the results discussed above, to avoid skiing-related injuries in the lower limbs, exercise to strengthen the quadriceps and hamstring muscles to balance their strength is necessary. In particular, exercise to strengthen the hamstring muscles is required.

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