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Development of hip protectors for snowboarding utilizing 3D modeling and 3D printing

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Abstract

The purpose of this study was to develop a highly comfortable 3D male hip protector using 3D modeling and printing technologies. The hip protector pads and patterns were devised using 3D human body shapes, and three types of pads were chosen in consideration of snowboarding motions. The three types of pads were as follows: first, the original type with no hole; second, an inner open type with an incision on the inside; and third, an outer open type, with an incision on the outside. Another variable of the protective pads was the material: 3D printed thermoplastic polyurethane (TPU) pad + ethylene–vinyl acetate (EVA) foam or only EVA foam. Six types of pad prototypes were 3D printed and evaluated for subjective wearing comfort. Subjective comfort, fit, activity comfort, and shock absorption were evaluated on an 11-point Likert scale. The study results showed that protectors printed using TPU material were not different from the results of 3D modeling. The evaluation results revealed that comfort, fit, and motion comfort were all negatively evaluated by subjects when wearing the original pad. While fit, comfort, and motion comfort were all positively evaluated by subjects when wearing the outer open-type pad, and comfort and motion comfort were positively evaluated by subjects when wearing the inner open-type pad. With respect to materials, pads made with the 3D printing (TPU) and EVA foam combination provided the best results in terms of overall comfort, buttocks comfort, and activity comfort.

Keywords: 3D modeling, 3D printing, Snowboard, Hip protector

Introduction

Snowboarding is one of the most popular extreme winter sports among members of the younger generation (Subic and Kovacs 2019). Snowboarding is not only popular in Korea but also globally (Kim et al. 2011; Swedberg et al. 2017). In the United States, snowboarding is still beloved with over two million active snowboarders between 2017 and 2018 (Weinstein et al. 2019). However, along with its popularity, accidents consistently and frequently occur on ski resorts (Kim and Chung 2016; Michel et al. 2010). The National Ski Areas Association (NSAA 2018) investigates and reports skiing and snowboarding injuries annually, and although there was a slight decrease during the 2018/19 season compared to the year before, the number of accidents was still high. Moreover, the accident rate was very high for men younger than 30, and the most common lower-extremity injuries for snowboarders involved the lower trunk (lumbar spine, pelvis, and hip). Previous international studies related to snowboards have mainly focused on injuries, with many analyzing the types and severity of injuries and causes of occurrence (Ishimaru et al. 2012; Mahmood and Duggal 2014; Schmitt and Muser 2014; Weinstein et al. 2019; Wijdicks et al. 2014). Ishimaru et al. (2012) identified several factors of snowboard injuries (age, gender, self-reported skill level, experienced seasons, experienced days) and analyzed their relationship to the usage of protective gear (helmet, elbow pads, wrist guards, backbone guard, hip pads, and knee pads) by studying 5561 snowboarders who had experienced injuries. The results showed that the use of hip pads decreased the overall risk of common snowboarding injuries. Most Korean studies of snowboarding have also focused on injuries (Hyun and Jung 2010; Jang 2018; Kang and Kang 2012; Kroncke et al. 2008; Kweon et al. 2007; Lee et al. 2007; Nam 2013). Kweon et al. (2007) researched and analyzed the causes of injuries in snowboarder patients who visited a resort infirmary and emphasized the need for regulations concerning accident prevention. Also, Nam (2013) analyzed the causes of injury by classifying them according to personal factors, environmental factors, and gear-related factors and suggested solutions for each cause. As can be seen from the above-mentioned studies, the reality of injuries and methods to prevent accidents were proposed. (Ekeland et al. 2019; Ishimaru et al. 2012; Maat et al. 2019), and usage of protective gear was considered essential in many studies (Ishimaru et al. 2012; Lee 2013; Michel et al. 2010). However, certain study results have revealed that many snowboarders do not wear protective gear (Kim 2017; Kroncke et al. 2008; Lee and Hong 2019) because commercial protective gear does not satisfy consumers in terms of comfort (Lee and Hong 2019). Therefore, the development of comfortable snowboard protective gear is necessary, but most studies have focused on snowboard clothing and not on snowboard protective gear (Liu et al. 2014; Dammacco et al. 2012; Ryu and Park 2006; Kim et al. 2011; Kim 2008).

Recently, the development of various 3D technologies such as 3D printing, 3D data, and modeling techniques have been in the spotlight. Consequently, there have been attempts to produce clothing and fashion products using 3D printing. Product development based on 3D human body data and 3D technology, in particular, is an efficient research method that can enhance body suitability and mobility, so prototype development has been carried out using this method (Gupta 2011; Kim et al. 2015; Lee et al. 2017). Gupta (2011) proposed an efficient method of designing and engineering functional clothing, stating that at the "garment design" stage of this method, the usage of a 3D human body shape, 3D technology, and 3D program was highly recommended. Furthermore, Lee et al. (2017) developed outdoor pants for males, with superior motion and body conformance compared to regular outdoor pants, using 3D human body and pattern technology. Kim et al. (2015) developed a 3D life jacket with heterogenous thickness, using a 3D human body shape, that achieved excellent wearing sensation and motional comfort.

Moreover, 3D printing has been actively applied to the manufacture of prototypes, as it does not require mock-up operation or mold production, resulting in a swift manufacturing process (Kim 2016; Jeong 2016). Therefore, there have been attempts to utilize the process to develop leg protectors, wrist protectors, and hip protectors (Kim 2016; Jeong

2016). With respect to protective gear developed using 3D body shape and 3D modeling, Milošević and Bogović (2018) modeled chest protectors for hockey players based on female human body data. Furthermore, Lee et al. (2015) developed leg protectors for baseball catchers optimized for movement using 3D printing, and the 3D pad manufactured utilizing 3D shapes achieved the best evaluation. Park et al. (2019) also developed a crotch protector for cycling using 3D printing technology, and the 3D pad achieved a superior evaluation regarding wearing sensation and fit during movement. Recently, Park and Lee (2019) developed fall impact protection pads using 3D printing technology, but no studies of snowboard hip protectors have been conducted. Jeon (2020) analyzed the muscle activation rate of subjects' lower body movement when riding snowboards using a 3D motion analysis system, EMG system, and acceleration sensors. As a result, when riding a snowboard, although external forces such as friction on snow, air resistance, and momentum, etc. were affected to a snowboarder, the centripetal force during the turn operation was most prominent. Especially, the velocity of the center of mass was generally 9.27 m/s but accelerated to 15.14 m/s during turning, which increased the centripetal force, along with the burden on the joints of the lower body. It was also suggested that such posture analysis may enhance athletic performance and prevent injuries while snowboarding. Furthermore, consideration must be given to the fact that snowboarding leads to different postures of falls compared to regular falls and primarily causes serious injuries given the high speed. Moreover, wearers must move and bend constantly for many hours while wearing hip protectors; therefore, evaluation is required to determine their comfort level.

This study therefore modeled male hip protectors in various shapes based on snowboarder motions and designed patterns using 3D human body data. The optimal shape and material for the snowboarding hip protector were suggested by conducting a subjective wearing evaluation.

Method

Experiment protocol

To develop the prototype for the snowboarding hip protector, an experimental process was carried out based on the steps depicted in Fig. 1. First, hip protector pads were 3D modeled using the Geomagic Design X program (3D Systems, Inc., Korea). Second, the 3D printing process was conducted using a 3D printer (CUBICON Single Plus 3DP-310F) and Cubicreator software. Third, 3D hip protector patterns fitted to the human body were designed using the Yuka CAD System (Youth Hitech Co., Ltd, Korea) and 2C-AN software (Jeong and Hong 2006; Lee and Hong 2005; Wu and Hong 2012). Subjective wearing comfort was evaluated to select the optimal prototype. The specific step-by-step method and variables are as follows.

3D modeling of the hip protector pad

The wearing position of the pad was set to the buttocks and two sides of the hip to protect the tailbone and os coxae. The mean curvature of the 3D human body was used to design the outer line of the pad. Three types of pad shapes were modeled (original, outer open, and inner open). The original type was modeled according to the designed outer line, the outer open type was modeled with the transverse rectangular

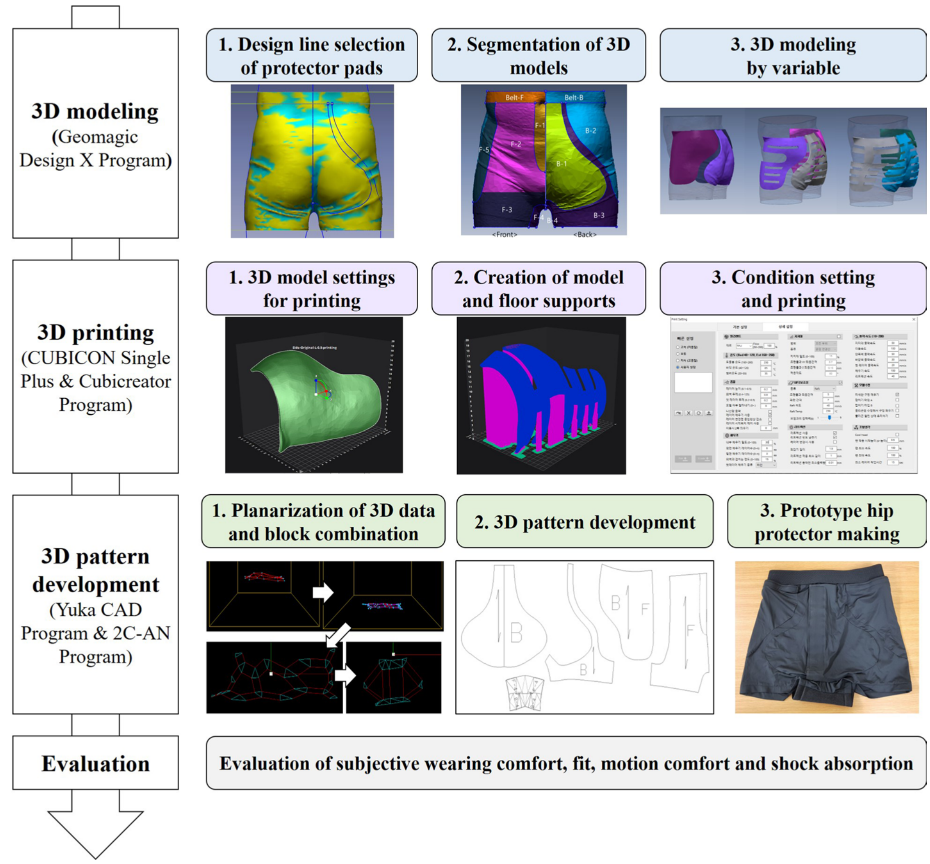

Fig. 1 Experimental process

hole open on the outer side, and the inner open type was modeled with the transverse rectangular hole located inside. The two open types were modified from the original to enhance motion comfort and thermal comfort, with modeling that allowed heat and sweat generated during exercise to be efficiently discharged to the outside through the regular holes. Changes in body surface and shape during snowboarding motions were considered. The thickness of the protectors was 5 mm.

3D printing of hip protector pads

Thermoplastic polyurethane (TPU), which displays high elasticity and shock absorption, was used as the 3D printing material, and 3D printing was carried out using a fused deposition modeling (FDM) 3D printer (CUBICON Single Plus 3DP-310F). The CUBICON Single Plus 3DP-310F used in this study prints with a 0.4 mm nozzle and has a maximum printing speed of 500 mm/s. Location precision is 6.25 μm, 6.25 μm, and 1.25 μm for the X, Y, and Z axes, respectively, with a layer resolution range of 150–300 μm and a minimum layer resolution of 100 μm. The required support fixture and platform were automatically produced using Cubicreator software, and complementary support fixtures were made by checking the printing path via the view mode.

For the 3D printing settings, the discharge temperature range was set to 210–240 °C, and the inner density was set to 30% to achieve flexibility. The printing speed was set to 40 mm/s and the thickness of the shell wall to 0.8 mm. After ensuring that the items were virtually printed well in the final view mode, the printing process was initiated. Each process took approximately 48 h.

Design and production of 3D hip protector patterns

To design the 3D hip protector pattern, design seam lines for segmentation were determined based on the mean curvature of mean 3D human data provided by Size Korea. The mean curvature was automatically generated using Geomagic Design X software (3D Systems, Inc.), and the results are shown in Fig. 2. The panels were then split based on the seam lines. The split panels were each flattened into 2D pieces using 2C-AN software and then the pieces were completed as 2D patterns using the Yuka CAD System (Youth Hitech Co. Ltd, Korea). The combination method employed in this study has been used and verified in many preceding studies (Jeong and Hong 2006; Lee and Hong 2005; Wu and Hong 2012). The hip protector was made from stretchable material, remaining unaltered in the wale direction but showing a 20% reduction in the course direction for a better fit (Ziegert and Keil 1988). Moreover, to facilitate insertion of the pad, it was designed to be inserted in a pocket on the protector.

Subjects and experimental protector pads

Modeling of the 3D hip protectors was processed based on average 3D human data of males in their 30 s, provided by the 7th Size Korea (2015). Subjects selected for evaluation were males in their 20 s and 30 s who enjoy snowboarding. The sizes of the selected subjects are shown in Table 1, and the experimental method was verified by the National

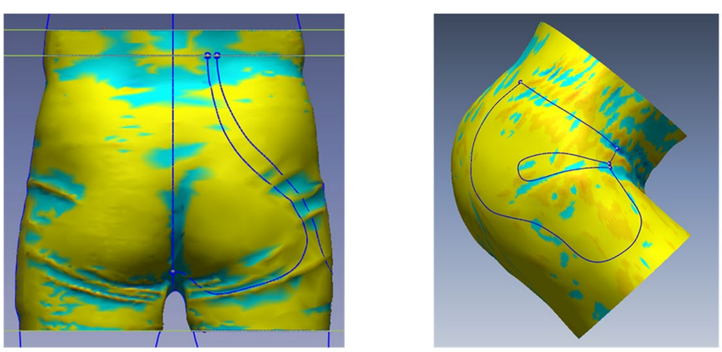

Fig. 2 Mean curvature of mean 3D human data

Table 1 Measurement of subject size (N = 10)

Subject	Age	Height	Waist	Hip	Weight
Mean ± SD	28.1 ± 4.0	173.9 ± 3.7 cm	85.3 ± 6.8 cm	101.4 ± 5.2 cm	72.4 ± 6.6 kg

SD Standard deviation

Institute in accordance with the Bioethics Policy IRB (Institutional Review Board) (201809-SB-139-01).

This study was conducted with 10 subjects for the experiment. Increasing the number of subjects would promote credibility of this experiment. However, Glodman claimed in a 2004 seminar that 6–10 subjects could produce adequate results for an experiment based on people. Moreover, a review of studies based on the human body (Lee et al. 2015, 2017; Park et al. 2019; Kim et al. 2015) shows that statistical results have been produced with 4–10 people.

Experimental variables for the hip protector pad were two types of materials (variable 1) and three types of shapes (variable 2). The two types of materials were (1) the formerly popularly used EVA pad (1.0 cm) and (2) the developed 3D printed pad (0.5 cm) combined with the EVA pad (0.5 cm). The three types of shapes selected were the original type, outer open type, and inner open type, as stated in the previous description of *3D modeling of the hip protector pad*. In total, six hip protectors were produced in accordance with the variables.

Subjective evaluation and analysis

Subjective evaluation was conducted to select the optimal protector's shape and material among the six developed hip protectors. Subjective wearing evaluation was performed in standing, sitting, and snowboarding postures. For evaluation in the standing and sitting postures, the pad's fit and wearing comfort in the overall region, region of the buttocks, and sides of the hips were measured on an 11-point Likert scale with reference to prior studies (Lee et al. 2017). For the wearing comfort evaluation, 0 point was given for very uncomfortable, 5 points for normal, and 10 points for very comfortable. For the fit evaluation, 0 point was given for very loose, 5 points for normal, and 10 points for very good fit. For the evaluation during snowboarding motions, the pad's fit, wearing comfort, and activity comfort in the overall region, region of the buttocks, and sides of hips were measured on an 11-point Likert scale (0 point: very loose/very uncomfortable, 5 points: normal, 10 points: very good fit/very comfortable). Shock absorption in the region of the buttocks was evaluated after having the subjects fall two or three times from a height of approximately 10 cm using an 11-point Likert scale (0 point: no shock absorption, 5 points: normal, 10 points: very good shock absorption).

The collected data were statistically processed using SPSS 24.0 statistics software. A repeated measure analysis of variance (ANOVA) and Bonferroni post hoc analysis were employed to check differences between the two variables (two types of materials and three shapes of protectors) and three types of postures (standing, sitting, and snowboarding motions) for evaluation. The standard for verification of statistical significance was $p < .05$.

Results

Modeling and printing of the 3D hip protector pad

The 3D modeling of the hip protector pad was performed using the right-side data of the 3D human data. The outer line was determined using the mean curvature of the human body data, and the 3D modeling process was performed after cutting the interior according to the design. The modeling of the whole shape of the protector was conducted by mirroring the right-side model to create the left-side part. The whole hip protector was modeled to a thickness of 5 mm using the extrude mode. As a result, the incision in each shape of the protector was determined as shown in Fig. 3. The length, upper width, and lower width of the original buttocks pad were 25.5 cm, 8.5 cm, and 37.0 cm, respectively. The length, upper width, and lower width of the side pad were 23.0 cm, 22.0 cm, and 13.0 cm, respectively. The height of the inner incision was 1 cm, and the width of each incision is presented in Fig. 3.

The 3D printed hip protectors are shown in Fig. 4. The sizes of the modeled 3D data and printed hip protector pads were observed to be identical, showing that the hip protectors were effectively materialized through 3D modeling and 3D printing.

The final six types of hip protector prototype were as shown in Fig. 5. The protectors were worn by a male mannequin with a waist circumference of 81.5 cm and hip circumference of 96.5 cm. The results showed that when both 3D printing pads reflecting the 3D human body shape and EVA pads were inserted in the hip protectors, the protectors fit the human body well compared to hip protectors with an EVA pad that was only 1.0 cm thick inserted.

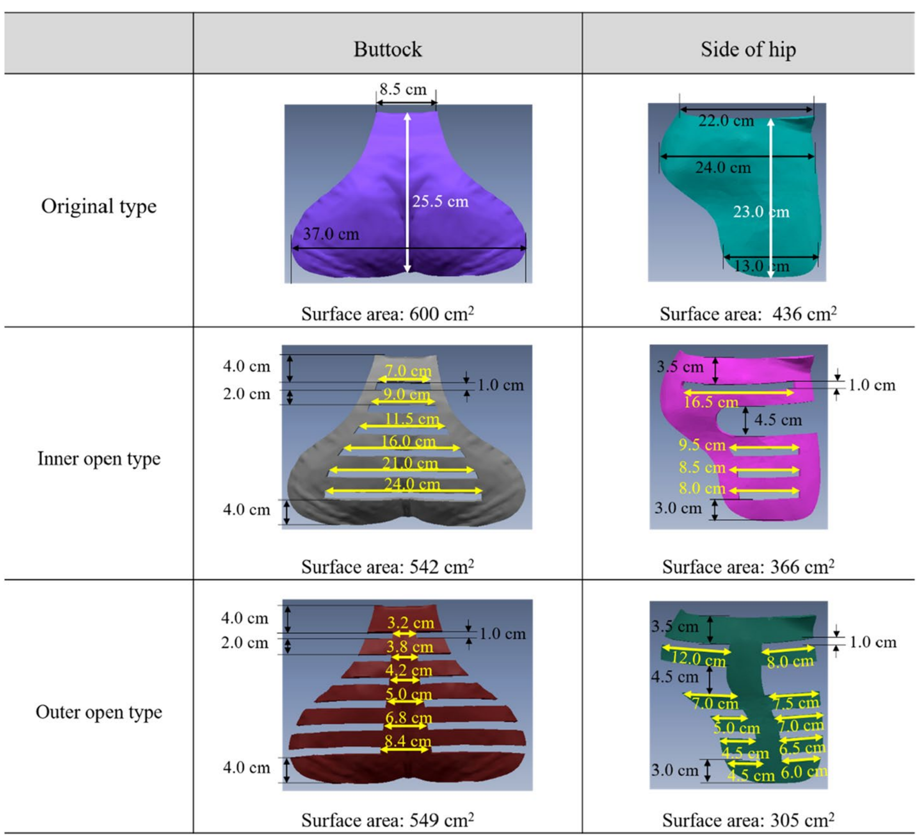

Fig. 3 Pad modeling sizes and incision shapes for hip protectors

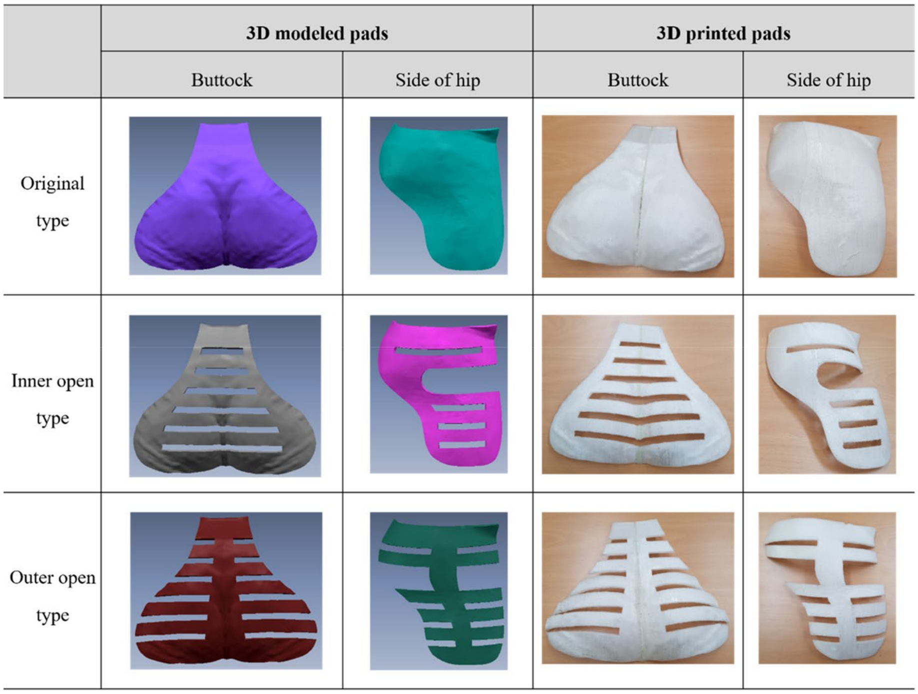

Fig. 4 Comparison of 3D modeled results and 3D printed results

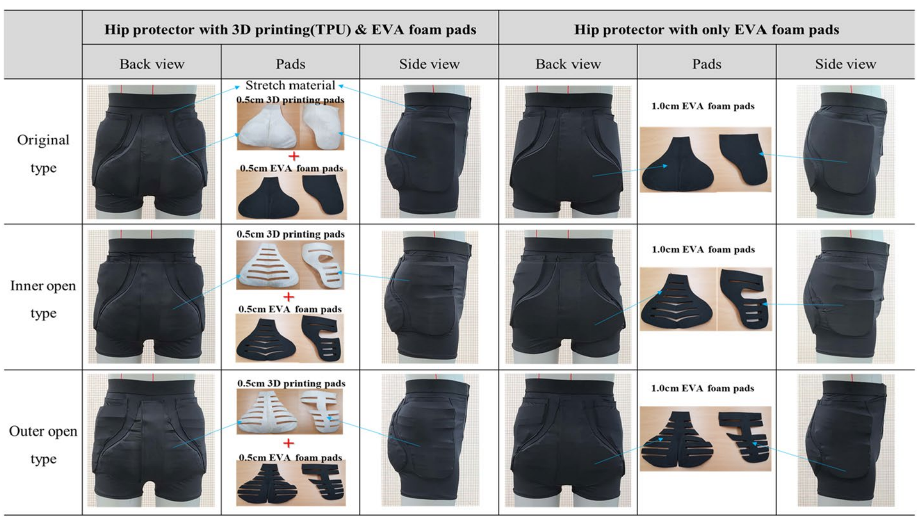

Fig. 5 Shapes of hip protectors and pads placed on a male mannequin

Wearing evaluation of hip protectors

Subjective wearing comfort

The repeated measures ANOVA results for subjective wearing comfort are presented in Table 2. The mean and SD (standard deviation) of subjective wearing comfort values depending on the material, shape, and test posture are shown in Table 3. There were significant differences in overall wearing comfort, depending on the material

Table 2 Subjective comfort depending on material, shape, and test posture (repeated measures ANOVA)

	Type III sum of squares	df	F	*p*-value
Overall wearing comfort				
Material	18.69	1	5.92	0.04
Shape	100.31	2	23.07	0.00
Posture	2.98	2	0.39	0.68
Material*Shape	12.98	2	1.69	0.21
Material*Posture	6.18	2	1.70	0.21
Shape*Posture	21.26	4	3.48	0.02*
Material*Shape*Posture	3.66	4	0.67	0.62
Side wearing comfort				
Material	0.27	1	0.17	0.69
Shape	85.14	2	22.56	0.00***
Posture	27.54	2	5.32	0.02*
Material*Shape	10.54	2	1.61	0.23
Material*Posture	2.88	2	1.75	0.20
Shape*Posture	3.72	4	1.63	0.19
Material*Shape*Posture	1.86	4	0.52	0.72
Buttocks wearing comfort				
Material	22.76	1	13.15	0.01*
Shape	43.01	2	12.14	0.00***
Posture	1.68	2	0.31	0.74
Material*Shape	17.41	2	2.62	0.10
Material*Posture	0.34	2	0.10	0.90
Shape*Posture	0.82	4	0.19	0.94
Material*Shape*Posture	5.29	4	0.99	0.43

df: Degree of freedom

and shape ($p < .05$, $p = .000$), and an interaction between shape and test posture was also observed ($p < .05$). The repeated measures ANOVA results for side wearing comfort were statistically different depending on the shape and test posture ($p = .000$, $p < .05$), while the repeated measures ANOVA results for buttocks wearing comfort showed differences depending on material ($p < .01$) and shape ($p = .000$).

Interaction between the protector shape and test posture in overall wearing comfort was observed, and the difference is depicted in Fig. 6. Lower comfort (4.7 points) was observed when sitting down while wearing the original-type pad, compared to sitting (7.2 points, $p < .01$), standing (7.1 points, $p < .01$), or motion (6.9 points, $p < .01$) while wearing the inner open-type pad. Moreover, sitting while wearing the original-type pad led to even lower comfort (4.7 points) than during motion while wearing the outer open-type pad (6.7 points, $p < .05$). Performing snowboard motions while wearing the original-type pad (4.7 points) led to lower overall comfort compared to standing (7.1 points, $p < .05$) or sitting (7.2 points, $p < .05$) while wearing the inner-type open pad. In other words, sitting or performing motions while wearing the original-type pad resulted in the lowest level of comfort, whereas sitting or performing motions while wearing the inner open-type pad showed overall superior comfort.

Since side-wearing comfort was observed to vary depending on the shape of the pad or the test posture, each statistical difference was compared using Bonferroni's post hoc

Table 3 Mean and SD of subjective comfort depending on material, shape, and test posture (N = 10)

Variable			Evaluation criteria					
			Overall wearing comfort		Side wearing comfort		Buttocks wearing comfort	
Material	Shape	Posture	Mean	SD	Mean	SD	Mean	SD
3D printing + EVA pad	Original	Standing	6.2	1.8	6.7	1.8	6.9	1.3
		Sitting	4.9	2.8	4.9	1.8	6.6	1.3
		Snowboard motion	5.3	1.8	5.4	1.6	6.7	1.6
	Inner open	Standing	7.9	1.4	7.8	1.3	7.8	1.2
		Sitting	7.5	1.1	6.7	2.2	7.5	1.0
		Snowboard motion	7.7	1.3	7.2	1.4	8.0	1.2
	Outer open	Standing	6.6	1.6	7.1	1.9	6.7	2.3
		Sitting	6.3	1.9	6.4	2.3	7.3	1.6
		Snowboard motion	7.6	1.6	6.4	2.5	7.1	1.7
EVA pad	Original	Standing	5.7	2.2	5.7	2.0	5.1	2.1
		Sitting	4.6	2.5	4.7	2.6	5.5	3.0
		Snowboard motion	5.1	2.4	5.6	2.5	6.0	1.5
	Inner open	Standing	5.8	1.4	7.0	1.4	6.6	1.3
		Sitting	6.9	1.7	6.5	1.6	6.8	1.6
		Snowboard motion	6.2	1.4	6.7	1.4	6.6	1.3
	Outer open	Standing	6.2	2.0	7.6	1.2	7.2	0.8
		Sitting	6.8	1.8	7.0	1.6	7.1	1.6
		Snowboard motion	6.9	2.0	7.1	1.8	7.3	1.5

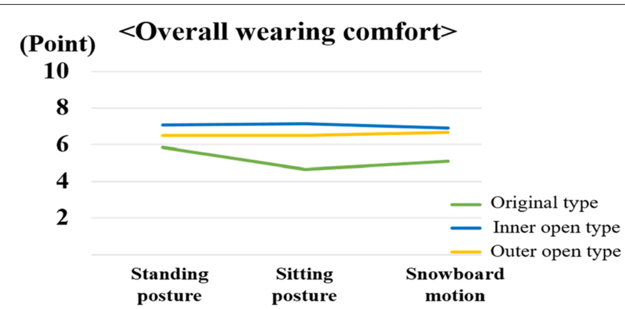

Fig. 6 Overall wearing comfort depending on shape and posture (Bonferroni post hoc analysis method)

test. The results showed that wearing comfort differed only depending on pad shape, as shown in Fig. 7. Side-wearing comfort was shown to be of an average level (average 5.5 points) when wearing the original-type pad. Meanwhile, better wearing comfort (average 7.0 points) was observed when wearing the inner open-type pad ($p < .01$). Furthermore, wearing the outer open-type pad also resulted in better wearing comfort than the original-type pad at an average of 6.9 points ($p = .000$).

Statistical differences for buttocks wearing comfort were observed depending on the material and shape, and they were compared using Bonferroni's post hoc test, as shown in Fig. 8. The results showed that the combination of the 3D printed pad + EVA pad (average 7.2 points) was significantly better than the EVA pad (average 6.5 points)

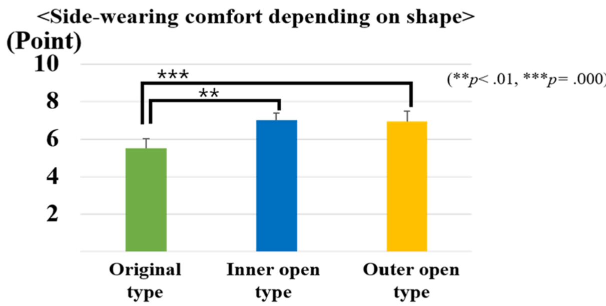

Fig. 7 Side-wearing comfort of pads depending on shape (Bonferroni post hoc analysis method)

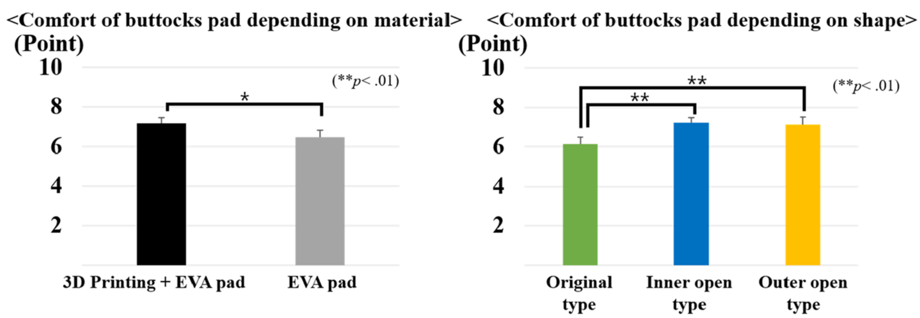

Fig. 8 Wearing comfort of buttocks pad depending on material and shape (Bonferroni post hoc analysis method)

($p < .01$) alone in buttocks wearing comfort. In addition, buttocks wearing comfort depending on pad shape showed an average level for the original-type pad with an average of 6.1 points and a higher level for the inner open-type pad with an average of 7.2 points ($p < .01$). The outer open-type pad (average 7.1 points) also had higher comfort than the original-type pad ($p < .01$).

Subjective fit

The subjective fit evaluation results depending on material (two types), shape (three types), and test posture (three types) when wearing hip protectors were observed, as shown in Table 4. Moreover, Table 5 depicts the mean and SD of subjective fit evaluation values depending on the material, shape, and test posture. In the overall fit evaluation, a significant difference was observed depending on the shape, and an interaction between shape and test posture was also detected ($p < .05$). The fit evaluation of the sides showed a statistical difference only in pad shape ($p = .000$). The fit evaluation of the buttocks showed meaningful differences depending on pad shape ($p < .05$) and test posture ($p = .000$).

In the overall fit evaluation by Bonferroni's post hoc test, no interaction between the protector shape and test posture was observed. On the other hand, in the overall fit evaluation by Bonferroni's post hoc test (Fig. 9), statistically significant differences were found only between pad shapes. In the case of wearing the original-type pad, the overall fit evaluation was an average level of a 5.5 points. On the other hand, the outer

Table 4 Subjective fit evaluation depending on material, shape, and posture (repeated measures ANOVA)

	Type III sum of squares	df	F	*p*-value
Overall fit				
Material	11.25	1	1.49	0.25
Shape	22.68	2	4.66	0.02*
Posture	2.88	2	1.96	0.17
Material*Shape	7.03	2	1.17	0.33
Material*Posture	1.03	2	0.84	0.45
Shape*Posture	6.96	4	3.43	0.02*
Material*Shape*Posture	3.13	4	2.00	0.12
Side fit				
Material	0.27	1	0.20	0.66
Shape	20.81	2	7.40	0.00***
Posture	1.38	2	0.55	0.59
Material*Shape	4.81	2	2.19	0.14
Material*Posture	1.91	2	1.99	0.17
Shape*Posture	7.69	4	2.13	0.10
Material*Shape*Posture	2.16	4	0.78	0.55
Buttocks fit				
Material	28.01	1	3.25	0.11
Shape	13.01	2	4.69	0.02*
Posture	33.14	2	12.00	0.00***
Material*Shape	7.48	2	1.77	0.20
Material*Posture	7.34	2	2.81	0.09
Shape*Posture	3.26	4	0.88	0.49
Material*Shape*Posture	1.52	4	0.81	0.53

open-type pad (average 7.3 points) was evaluated more positively than the original-type pad.

Statistical differences in side-fit evaluation of hip protectors were observed depending on pad shape, and they were compared using Bonferroni's post hoc test, as shown in Fig. 10. The results showed that the outer open-type pad (average 7.6 points) had a better fit than the original-type pad (average 6.8 points) ($p < .05$).

The buttocks fit evaluation of the hip protector depending on pad shape and test posture is shown in Fig. 11. With respect to pad shape, the outer open-type pad (average 7.4 points) was superior to the original-type pad (average 6.7 points) ($p < .05$). With respect to fit depending on test posture, the standing position was evaluated with an average of 6.5 points, while the sitting position and snowboard motion were evaluated with an average of 7.6 points ($p < .01$) and 7.0 points ($p < .05$), respectively.

Subjective activity comfort

The results of the repeated measures ANOVA of subjective motion comfort depending on protector pad material (two types) and pad shape (three types) during snowboard motion are shown in Table 6. Furthermore, Table 7 showed the mean and SD of subjective motion comfort values depending on the material and shape. In terms of overall activity comfort, there was a significant difference depending on pad shape ($p = .000$).

Table 5 Mean and SD of subjective fit evaluation depending on material, shape, and test posture (N = 10)

Variable			Evaluation criteria					
			Overall fit		Side fit		Buttocks fit	
Material	Shape	Posture	Mean	SD	Mean	SD	Mean	SD
3D printing + EVA pad	Original	Standing	6.6	1.2	6.9	1.4	6.4	1.1
		Sitting	7.0	1.8	7.2	1.6	7.8	1.2
		Snowboard motion	6.4	1.9	6.4	2.2	7.4	1.3
	Inner open	Standing	7.0	1.2	7.3	1.2	6.6	1.0
		Sitting	7.8	0.8	7.7	1.1	8.3	0.9
		Snowboard motion	8.0	0.7	7.7	.8	7.8	0.6
	Outer open	Standing	7.1	1.1	7.6	1.3	7.1	1.0
		Sitting	7.1	1.5	7.0	1.5	7.6	1.5
		Snowboard motion	7.6	1.3	7.7	1.3	7.8	0.8
EVA pad	Original	Standing	6.3	1.9	7.0	1.8	5.9	1.7
		Sitting	6.1	2.4	6.4	1.6	7.0	2.1
		Snowboard motion	6.2	2.0	6.8	1.5	5.9	1.7
	Inner open	Standing	6.1	1.3	6.9	1.7	6.0	1.3
		Sitting	6.9	1.3	7.1	1.3	6.9	1.8
		Snowboard motion	6.8	1.5	7.3	1.4	6.2	1.7
	Outer open	Standing	7.4	1.9	8.0	1.3	7.1	1.5
		Sitting	7.3	1.9	7.3	1.5	7.8	1.4
		Snowboard motion	7.0	1.8	8.0	1.2	6.9	2.0

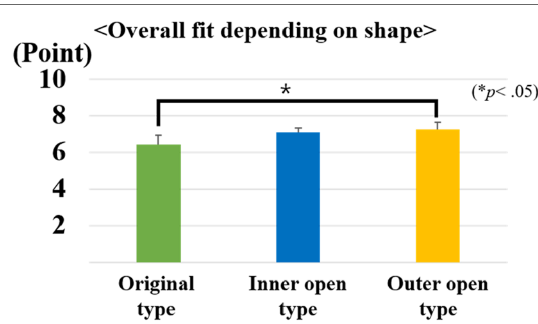

Fig. 9 Overall fit evaluation depending on shape (Bonferroni post hoc analysis method)

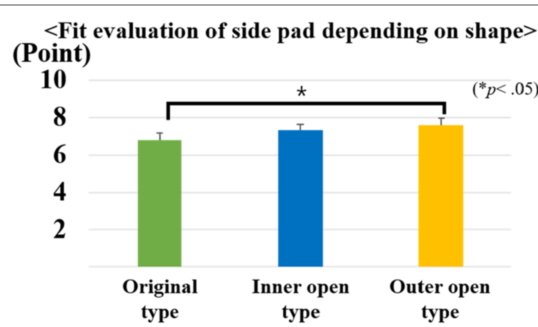

Fig. 10 Side-fit evaluation depending on pad shape (Bonferroni post hoc analysis method)

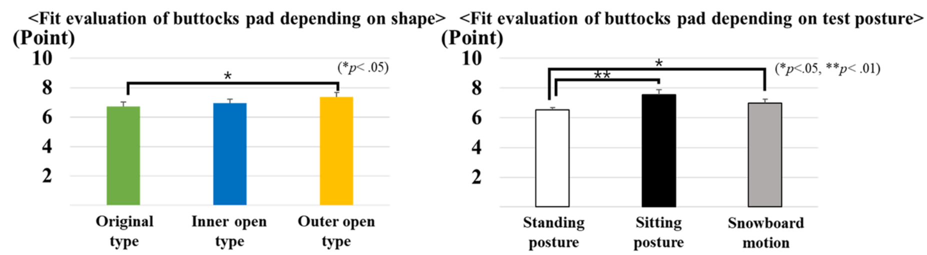

Fig. 11 Buttocks fit evaluation depending on shape or test posture (Bonferroni post hoc analysis method)

Table 6 Subjective motion comfort depending on material and shape (repeated measures ANOVA)

	Type III sum of squares	df	F	*p*-value
Overall mobility				
Material	7.35	1	4.46	0.06
Shape	42.23	2	16.22	0.00***
Material*Shape	3.70	2	0.78	0.47
Side mobility				
Material	1.35	1	0.63	0.45
Shape	37.20	2	25.49	0.00***
Material*Shape	2.80	2	1.77	0.20
Buttocks mobility				
Material	16.02	1	11.25	0.01*
Shape	17.50	2	4.52	0.03*
Material*Shape	2.23	2	0.49	0.62

Table 7 Mean and SD of subjective comfort depending on material and shape (N = 10)

Variable		Evaluation criteria					
		Overall mobility		Side mobility		Buttocks mobility	
Material	Shape	Mean	SD	Mean	SD	Mean	SD
3D printing + EVA pad	Original	5.6	2.4	5.6	1.5	7.0	2.3
	Inner open	7.8	1.3	7.5	1.8	8.1	1.1
	Outer open	7.4	1.5	7.3	1.8	7.9	1.6
EVA pad	Original	5.2	1.6	5.5	2.2	5.8	1.8
	Inner open	6.4	1.6	6.6	2.1	6.7	1.7
	Outer open	7.1	2.5	7.4	1.8	7.4	2.3

There was also a difference in side pad motion comfort depending on pad shape ($p = .000$), while buttocks pads showed statistical differences depending on material or shape ($p < .05$).

The Bonferroni's post hoc test results comparing the difference in overall motion comfort depending on pad shape (Fig. 12) showed that the original-type pads were rated at an average of 5.4 points, while the inner open-type (average 7.1 points) and outer open-types (average 7.3 points) had higher evaluations ($p < .01$).

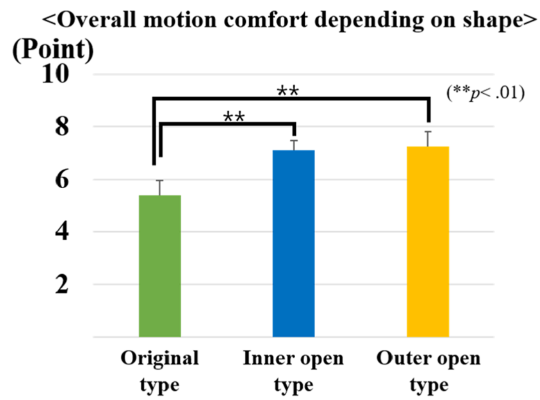

Fig. 12 Subjective motion comfort depending on shape while snowboarding (Bonferroni post hoc analysis method)

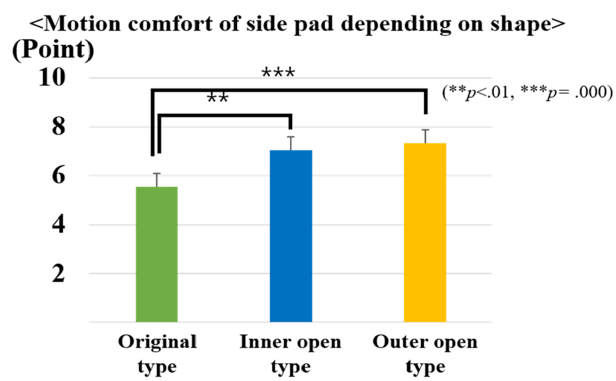

Fig. 13 Subjective motion comfort of side pads depending on shape (Bonferroni post hoc analysis method)

Motion comfort in the side pads depending on pad shape was also compared using Bonferroni's post hoc test. The results are shown in Fig. 13. Outer open-type pads (average 7.4 points) were rated higher in motion comfort than original-type pads (average 5.6 points) ($p = .000$). Moreover, inner open-type pads (average 7.1 points) were rated higher in motion comfort than original-type pads ($p < .01$).

The results of motion comfort values in the buttocks pad (Fig. 14) showed statistical differences depending only on pad material ($p < .01$). The combined pads with the 3D printed pad and EVA pad (average 7.7 points) were better rated in terms of motion comfort than the EVA pad (average 6.6 points) ($p < .01$) alone.

Subjective shock absorption

The repeated measures ANOVA results of subjective shock absorption while wearing buttocks pads during snowboard motion depending on material (two types) and pad shape (three types) showed an interaction between material and shape ($p = .000$), as presented in Table 8. Additionally, the mean and SD of subjective shock absorption values depending on material and shape are shown in Table 9. However, the results of

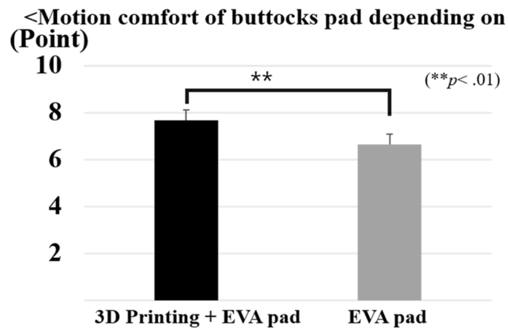

Fig. 14 Subjective motion comfort of buttocks pad depending on material (Bonferroni post hoc analysis method)

Table 8 Shock absorption of buttocks pad depending on material and shape (repeated measures ANOVA)

	Type III sum of squares	df	F	*p*-value
Shock absorption of buttocks pad				
Material	1.35	1	0.41	0.54
Shape	1.20	2	0.32	0.73
Material*Shape	7.60	2	4.54	0.03*

Table 9 Mean and SD of subjective comfort depending on material and shape (N = 10)

Variable		Evaluation criteria	
		Shock absorption of buttocks pad	
Material	Shape	Mean	SD
3D printing + EVA pad	Original	7.5	1.7
	Inner open	7.3	1.1
	Outer open	6.8	1.8
EVA pad	Original	6.8	1.6
	Inner open	6.4	1.5
	Outer open	7.5	1.6

the Bonferroni's post hoc test comparing differences depending on material and shape showed no statistical difference.

Conclusion and discussion

The purpose of this study was to develop a hip protector that fits snowboarders comfortably, based on 3D modeling and printing. The results are as follows:

First, three types of pads were modeled to protect the sides of the hips and buttocks using 3D human body data. The three protector pad types were the original type, inner open type with an internal incision, and outer open type with an external incision. The modeled pads were 3D printed using TPU, and the sizes of the printed pads were identical to each of their models. It was therefore determined that 3D printing use was a very effective way to develop 3D protective pads modeled on the shape of the human body.

Second, an optimal hip protector pad was suggested through subjective evaluation. All six hip protector pads were evaluated depending on shape (three types) and material (two types: EVA pad 1.0 cm; combined pad with 3D printing (0.5 cm) and EVA (0.5 cm). The pads were each rated in terms of wearing comfort, fit, motion comfort, and shock absorption in the standing posture, sitting posture, and snowboard motion postures. In the evaluation of pad shape, the original-type pad was rated the worst in terms of wearing comfort, fit, and motion comfort, while the outer open-type pad was highly rated in terms of fit, wearing comfort, and motion comfort, and the inner open-type pad was highly rated in terms of wearing comfort and motion comfort. Especially, the outer open-type pads were better rated in terms of fit than the original-type pads. The fit of the buttocks pads was rated better for the sitting and moving positions because the hip protectors were developed based on the 3D human body shape and movements, and the structure of the 3D pads was maintained, even for the sitting posture and motion positions. The outer open-type pads, in particular, were highly evaluated in terms of fit owing to the structural movability of the pads. The evaluation of the material showed that the protector pad that combined 3D printing (TPU) and EVA foam was rated higher than the only EVA foam pad in terms of comfort and motion comfort of the whole and of the buttocks.

In conclusion, the 3D printed pads modeled with reference to the shape of the 3D human body were superior in terms of comfort. Moreover, the open type-pad showed superior comfort, fit, and motion comfort to the original-type pad. With continued advances in 3D printing technology, print speed will become much faster, thus enabling the manufacture of personalized pads, leading to greater comfort. The results and methods of this research could be utilized in the development of various protector pads in 3D form and a protocol for the production of personalized pads in the future. Furthermore, these protocols can be applied as source technology in the field of clothing grafted with 3D printing and applied in diverse ways in the clothing industry. Moreover, 3D printing technology will become established as the leading technology in the clothing market, which is expected to be applicable in academia as well. However, in this study, research on the relationship between heat and comfort during long-term wear or exercise was not conducted; further research on these issues must therefore take place. Additional research is also necessary to produce a more objective investigation of protectors and field tests measuring the level of comfort of the new open-type protector pads compared to the original type, including the ease with which sweat is released. Moreover, application of new materials with better shock absorption and evaluation of their performance should be carried out as well. Furthermore, snowboard protectors for females should also be developed in future studies by applying the protocol established in this study.

Abbreviations

EVA: Ethylene-vinyl acetate; TPU: Thermoplastic polyurethane.

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Authors' contributions

HL carried out all the experimental work under the supervision of the KHH performed the analyzing data and drafting the manuscript in conjunction with HL and KHH. Both authors read and approved the final manuscript.

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Availability of data and materials

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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