Fashion and Textiles

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Cycling knee brace design analysis using 3D virtual clothing program to assess clothing pressure distribution and variance

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Abstract

This study analyzed the functional design by investigating the distribution of clothing pressure of cycling knee brace using a three-dimensional virtual clothing program. Based on the average body size of Korean men in their 40 s, clothing pressure in wearing and cycling condition were collected on five knee brace products. According to the results, bonding fabric products had a high possibility of increasing inconvenience, as they had a higher clothing pressure at all measurement points and soared in motion application. It could be adjusted differently depending on the location by mixing materials or using details, so the design with thick pile fabric or velcro strap fastening added more pressure to the lower part of the knee. The length and circumference size also affected the clothing pressure. The design with tight upper and lower circumference pressured excessively the legs and rolled up and clumped together, while the one with loose lower circumference lacked the sufficient strength to support the knees. Also, the design with a curved outline due to the difference in the length of the front and back, increased the clothing pressure on the lower thigh or the upper calf. Therefore, the functional design of cycling knee braces requires comprehensive consideration of material thickness and structure, detailed size of length and circumference, fastening details, to reduce the pressure at the center and top of the knee and to support the lower part with proper pressure, as reflecting the pressure on the body location that come into contact during the motion.

Keywords: Cycling, Knee brace, Functional design, 3D virtual clothing, CLO 3D

Introduction

During the COVID-19 Pandemic in 2019–2020, cycling use increased in the United States and in European Union (EU) countries; there was an average increase of 16% in the United States and 8% in EU countries (Eco-Counter, 2021). It logical to link the increase in cycling during the pandemic to demand for an alternative means of daily transportation to replace public transportation. However, the main motivation for cycling during this period was reportedly to improve mental health and physical fitness (Peopleforbikes, 2021). Weekend cycling in particular increased sharply because people took up cycling as a form of exercise and recreation (Buehler & Pucher, 2021).

Cycling is a highly recommended leisure sports that contributes to health, but there is always a risk of injury. The type of injury to which cyclers are the most prone is knee injury, and it has been reported that 40–60% of cyclists are affected by knee pain (Wanich et al., 2007). Functional clothing products called knee braces, knee pads, or knee guards are commonly worn to reduce the likelihood of knee injuries and relieve pain during cycling. Previous studies related to knee braces mainly focused on how wearing them affected athletes' performance, as well as the rehabilitative and preventive effects of it on knee injuries (Fleming et al., 2000; Pietrosimone et al., 2008; Rishiraj et al., 2009). The results of these studies are contradictory, and further studies are needed on the efficacy of wearing knee braces to prevent injuries and for rehabilitation (Fleming et al., 2000; Risberg et al., 1999; Rovere et al., 1987; Tiggelen et al., 2004). Extant studies are limited to specific cases of extreme exercise, or they used subjects that were not in a healthy state; research on recreational products often worn in daily life has been insufficient.

Knee braces are supposed to prevent damage to the flexible soft tissue around the knee by reducing excessive tension and ligament shock response when the knee is under a high load (Fleming et al., 2000; Pietrosimone et al., 2008). Knee braces need to be designed with differentiated pressure points to avoid applying pressure to the center of the knee; the lower part of the knee must be supported to prevent excessive forward movement of the tibia against the femur (DeVita et al., 1996; Lee et al., 2015). At the same time, the knee brace must not exert excessive pressure so as to avoid constricting blood flow and motor ability. Baek et al. (2022) reported that skin pressure increased by three times while wearing the knee braces, but the value was mild enough not to restrict skin blood flow, knee joint movements, or induce pressure discomfort. And increases in pressure from wearing knee guards were less manifested during dynamic motions (e.g., kicking, jumping) when compared to static positions (e.g., sitting, standing). However, high pressure may not be continuously applied equally because the cycling movement is a motion of sitting and rotating the legs, and the pressure for each location can be changed according to the movement of bending and stretching the legs. Since compressive clothing has different degrees of positive pressure depending on their use (Kim & Park, 2022), research on clothing pressure of knee braces for cycling needs to be investigated focusing on their movements.

There are not many knee braces commercialized for cycling, so general products are usually used for cycling. But it is difficult for consumers to choose products suitable for their body type because the pressure location and degree are different as the material, details, length, or circumference vary depending on the design. According to a study by Lee and Do (2023) on compressed leggings, clothing pressure was influenced more by circumference than length, and products with small circumference showed relatively high clothing pressure at each location. However, knee braces on the market have different designs and sizes which are not standardized, making it difficult to analyzing on the same standards.

Therefore, this study used CLO 3D, a three-dimensional (3D) virtual clothing program that is increasingly utilized as actual fit can be estimated through the measurement of clothing pressure by location (Kim & Lee, 2023), to identify clothing pressure distribution and movement-induced changes while wearing various knee braces currently used

Table 1 Information about the analyzed products

Type	Number of reviews	Grade	Size (cm)		Price (KRW)	Fabric composition	Manufacturing country
Product A	37,288	4.5	Free (One size)		12,900	Nylon, Lycra	China
Product B	8618	4.7	Product size	Knee circumference	39,700	Nylon, Polyester, Poly Urethane	Vietnam
			M	33–37			
			L	38–42			
			LL	43–47			
			3L	48–52			
Product C	3421	4.8	Product size	Mid-thigh circumference	49,500	Unconfirmed	Korea
			F	42–52			
			L	53–63			
Product D	1308	4.7	Product size	Knee circumference	4290	Poly Urethane	Korea
			S	28–32			
			M	33–39			
			L	40–44			
Product E	2285	4.8	Product size	Calf circumference	49,000	Styrene	China
			XS	28–32			
			S	33–37			
			M	38–42			
			L	42–49			

for cycling activities. The research entailed analyzing the design of each product to identify its wearing conditions and effects. Though it is important for sports clothing products to have a distinguishable aesthetic design, it is essential for the design to be functional. This paper intends to provide consumers with useful information for choosing knee braces for cycling, and it will provide references that could serve as guidelines for developing designs that increase the practical value of knee braces.

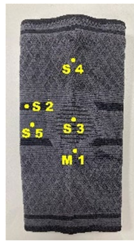
Methods

Study subjects' product-specific characteristics

This study targeted the cycling knee braces in Korea that received a high number of consumer reviews. The analysis targets were selected based on a keyword search on Naver Shopping, which has the highest market share in the Korean online shopping market (Lee, 2022). The search terms used were "cycling knee brace". Five different knee brace designs were adopted from among the top-ranked products returned in the search results, according to the number of reviews and ratings, as well as the sales quantity (Table 1).

As shown in Table 2, Product A is made of knit material and is cylindrical in shape, and the degree of stretch varies depending on the part of the garment, as different knit structures are placed at different locations on the wearer's knee. The main material, M1, and the same 1×1 rib stitch knit with different color, S2 cover an X-shaped area and comprise the overall frame. S3 covers the front and back of the knee, and S4 covers the wide side of the body plate. S5 is at the center of the side and the back, an area that folds when the wearer bends their leg. All the aforementioned parts are stretchable; M1 and S2 have the highest degree of stretch, followed by S4, S3, and S5 in descending order.

Table 2 Products' material composition and size

Type	Images		Length	Circumference	Material type
Product A	 Front	 Back	Top: 26.5 Bottom: 26.5	Top: 30.0 Bottom: 25.0 Mid-knee: 27.5	M1: 1 × 1 rib stitch knit (1) S2: 1 × 1 rib stitch knit (1) S3: 1 × 1 rib stitch knit (2) S4: Jacquard knit S5: Varied rib stitch knit
Product B	 Front	 Back	Front: 19.5 Back: 19.0	Top: 34.0 Bottom: 27.0 Mid-knee: 31.0	M1: Single jersey S2: Laminated fabric S3: Pile fabric S4: Elastic binding tape
Product C	 Front	 Back	Front: 25.0 Back: 20.0	Top: 31.0 Bottom: 31.0 Mid-knee: 34.0	M1: Punched laminated fabric S2: Mesh fabric S3: Elastic binding tape
Product D	 Front	 Back	Front: 30.0 Back: 26.5	Top: 33.0 Bottom: 30.0 Mid-knee: 31.0	M1: 1 × 1 rib stitch knit (1) S2: 1 × 1 rib stitch knit (3) S3: Varied rib stitch knit
Product E	 Front	 Back	Front: 24.5 Back: 18.5	Top: 34.0 Bottom: 30.0 Mid-knee: 31.0	M1: Laminated fabric S2: Elastic binding tape

Unit of measurement for length and circumference: cm

Product B mainly comprises a thin single jersey fabric M1. The upper surface of the front plate and the bottom surface of the rear plate are faced with S2 laminated material on the inside. The overlay sewn on the back plate is the same laminated fabric, and the overlay extends and is wound around and fixed, by means of an adjustable Velcro strap, to S3, which is a pile fabric patched below the knee. The seam running along the circumference of the knee brace is bound with an elastic tape, S4. Product C has an open knee design, and the wearer can adjust its circumference by wrapping it around their leg and securing it with Velcro tape. The main material, M1, is a perforated bonding material, and the rear plate has thin mesh S2 material on the upper side along the incision line below the seam that passes over the rear of the wearer's knee. The entire seam width is bound with an elastic tape, which was same with S4 in Product B. Product D is a cylindrical knit material similar to Product A, but it is considered to be a simple design because the structure is nearly uniform. The main material, M1, is similar in thickness and stretch to M1 in Product A, and S2 at the knee and S3 at the center of the side and rear are thinner and more stretchable in descending order. Finally, Product E is designed with a curved longitudinal incision line; it comprises the thickest and stiffest laminated material, M1, and the seam allowance is bound with S2, which is like S4 in Product B. Products A and D are long types, Products B and D are short types, and Products C, D, and E are shorter in the back than in the front. Regarding circumference, Product C is the largest, and Product A is the smallest. Product B has a relatively small circumference on its lower half compared to its upper half. The material of each product in Table 1 is based on the information provided on the sales site, which is not confirmed.

In this study, the product size was selected based on the average body size of Korean men in their 40 s. They reportedly have the second-highest cycling frequency in Korea, after male teenagers (Ministry of Culture, Sports and Tourism, 2022). Based on the average dimensions of men in their 40 s provided by the Size Korea's Korean Human Dimension Survey, this study selected Products B and C in size large (L), Products D and E in size medium (M), and Product A in free size that only comes in one size. Because the recommended sizes were different for each product, the product size was selected based on the standard body size in the 40 s. The wearer dimensions referred to in the selection process were as follows: mid-thigh circumference in the range of 520.95–531.61 mm, knee circumference in the range of 378.66–384.2 mm, and calf circumference in the range of 384.9–386.98 mm.

Patterns were produced based on the actual selected products, and a constructive line was added to distinguish the location of the different materials comprising the knit products. Data for each pattern were created in a dxf file using a digitizer, and the data correction process was performed via contrast with the real pattern (Fig. 1).

Measurement of clothing pressure on 3D virtual clothing simulation

Simulations using CLO 3D program were conducted by applying each product's dxf pattern file, and while each product was in use, changes in the pressure each part exerted during cycling were measured. Due to the limited material information provided on the product website and the limited accurate measurement of the physical properties of the material used in the product, the fabric files provided by CLO 3D with the most similar structure, composition, and thickness were applied during the simulation process. In order to compare the stress difference by location between products rather than examining each product independently, the same fabric file was applied to the products with the same material type, but its thickness and stretch / stiffness of weft and warp were relatively adjusted. In the case of knit products, the value of thickness and stretch / stiffness of the sub-material was relatively adjusted based on M1 by using the same fabric

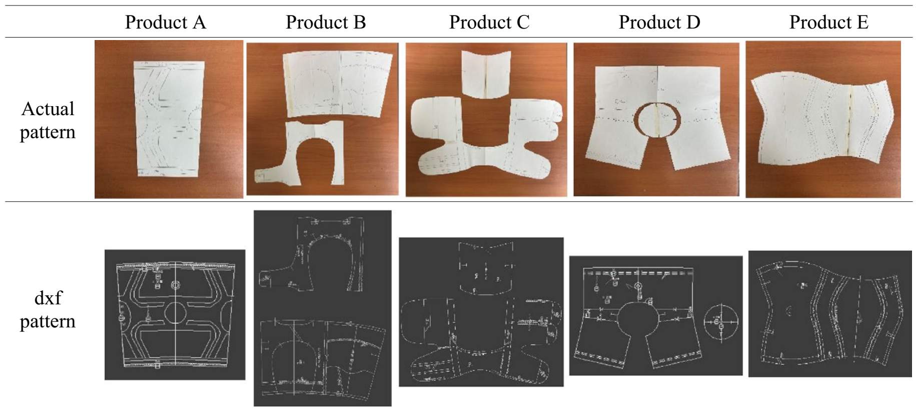


Fig. 1 Actual patterns and dxf pattern file images for each product

file without distinguishing its structure (Table 3). For example, for Product A, the fabric file of M1 was applied to sub-materials, and its stretch / stiffness was adjusted to 70% for S3 and 50% for S4 and S5 according to the difference in elasticity. The same fabric file was applied to the M1 for Product D, a knit material product, and the thickness valued of the relatively thinner S2 and S3 were adjusted to 50%, and the stretch / stiffness values each were set high at 150% and 200%. For Products B, C, and E, where laminated fabric is used, detailed values were adjusted based on the laminated material S2 in Product B. The thicker and punched laminated material M1 of Product C was adjusted to a thickness of 200% and a density of 50%, and Product E, which has the thickest laminated material, was adjusted to be 300% thicker.

For the simulation, the avatar was constructed to reflect the average size of Korean men in their 40 s using 3D human body shape data provided by Size Korea. Clothing pressure measurement positions included high-pressure peripheral positions along the center of the front part of the knee, as well as the knee pit, and the circumferences of the top and bottom bands of each knee brace (Table 4). In this study, the front part of the knee was considered to comprise the center (FK-C), upper center (FK-UC), and lower center (FK-LC), and the knee pit was considered to comprise the center (BK-C), lower center (BK-LC), and lower inner (BK-LI) areas. The upper part of the band was considered to comprise the front center (UB-FC), front inner (UB-FI), front outer (UB-FO), and rear center (UB-BC). The lower part of the band was considered to comprise the front center (LB-FC), rear center (LB-BC), and back inner (LB-BI) areas. Depending on the design, the center of the back overlaid cover (BO-C) was added to Product B's measurement positions, and the center of the front knee was excluded for Product C.

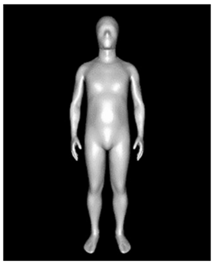
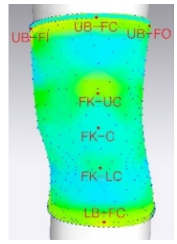
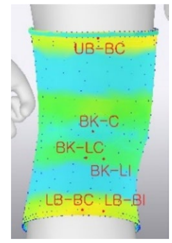
In this study, clothing pressure analysis was performed on the 3D virtual clothing process, with a focus on the stress data the CLO 3D program provided. In CLO 3D, clothing pressure is presented as a numerical stress value accompanied by a color distribution chart, thereby facilitating evaluation of the degree of pressure exerted on each body part when wearing the garment (Kwon et al., 2021). Stress is expressed

Table 3 Information about each product's material as applied in the 3D virtual clothing simulation

		Material type	Fabric composition	Thickness (mm)	Density (g/s^2)	Stiffness-Weft (g/s^2)	Stretch-Weft	Stiffness-Warp (g/s^2)	Stretch-Warp
Product A	M1	1 × 1 rib stitch knit (1)	87% polyester, 13% elastic	1.03	303.54	103,796	27	84,383	24
	S2	1 × 1 rib stitch knit (1)			303.54	103,796	27	84,383	24
	S3	1 × 1 rib stitch knit (2)			303.54	60,000	19	50,000	17
	S4	Jacquard knit			303.54	35,000	14	25,000	12
	S5	Varied rib stitch knit			303.54	35,000	14	25,000	12
Product B	M1	Single jersey	79% polyester, 21% elastic	0.37	83.33	30,335	13	30,950	13
	S2	Laminated fabric	95% polyester, 5% elastic	1.16	344.95	709,278	60	546,345	58
	S3	Pile fabric	Unconfirmed	0.90	212.12	65,384	20	152,007	32
	S4	Elastic binding tape	79% polyester, 21% elastic	0.37	83.33	30,335	13	30,950	13
Product C	M1	Punched laminated fabric	95% polyester, 5% elastic	2.32	172.48	709,278	60	546,345	58
	S2	Mesh fabric	Unconfirmed	0.37	128.79	393,816	56	258,746	43
	S3	Elastic binding tape	79% polyester, 21% elastic	0.37	83.33	30,335	13	30,950	13
Product D	M1	1 × 1 rib stitch knit (1)	87% polyester, 13% elastic	1.03	303.54	103,796	27	84,383	24
	S2	1 × 1 rib stitch knit (3)		0.52	303.54	240,000	41	190,000	36
	S3	Varied rib stitch knit		0.52	303.54	370,000	54	310,000	48
Product E	M1	Laminated fabric	95% polyester, 5% elastic	3.48	344.95	709,278	60	546,345	58
	S2	Elastic binding tape	79% polyester, 21% elastic	0.37	83.33	30,335	13	30,650	13

as the degree of force that affects a particular area as well as body volume and movement on the avatar when dressed, and the closer the number is to zero, the less pressure there is on the avatar. Lower pressures are shown in blue, and higher pressures are in red (Hong et al., 2015; Kwon et al., 2021). A cycling motion file provided by MIXAMO was applied to understand changes in clothing pressure for each product according to the avatar's state of motion, particularly cycling movements, and the

Table 4 Avatar and clothing pressure measurement locations using Korean 40-something males' average measurements

Avatar image	**Avatar details**		**Clothing pressure measurement location**	
	Body part criteria	Dimensions (mm)		
	Stature	1718.11		
	Knee height	443.00		
	Knee circumference	36.62		
	Calf height	327.00		
	Calf circumference	377.84		
	Thigh circumference	705.10	Front	Back

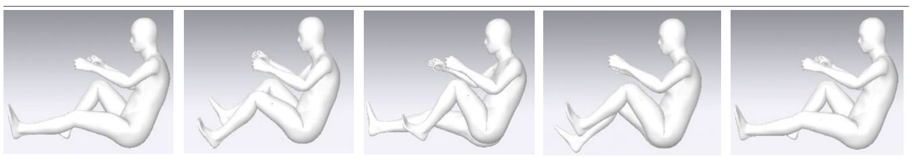


Fig. 2 Frame-by-frame motion changes in cycling motion files

state of the clothing. As shown in Fig. 2, the cycling motion file simulates the avatar bending and straightening each leg in turn and rotating them once. The entire operation was divided into a total of 200 frames, and stress values were collected for each measurement position every 10 frames. The avatar's left leg, where the product was being worn, began in an extended position in Frame 0 and was the most bent in Frame 100; the avatar was pedaling with his legs straight in Frame 200.

Results

Stress distribution by product

Figure 3 shows simulation images and stress distribution in 3D virtual clothing for each product. For Product B, it was difficult to measure the stress on the inner back of the bottom band (LB-BI) and the rear parts of the knee because the back cover tightened, folded, and clumped together. Because Product B's bottom circumference is smaller than that of Product E, which is similar to Product B in length, the knee guard could have rolled up above the calf. The highest and lowest stress positions were different for each product. Products A and D, which are made of knit materials, showed low stress. On the other hand, Products C and E, which are made of thick laminated materials with low elasticity, showed high stress. For all products, the highest stress point was on the back panel; specifically, for Products D and E, the highest stress point was the rear center of the upper band (UB-BC), and for Product C, it was the rear center of the lower band (LB-BC). For Product A, the aforementioned two points had the highest stress, and the actual values for both were the same. For Product B, the center of the back overlay (BO-C) had the highest stress (Table 5). Regarding stress around the front of the knee, Products A, B, and D had relatively low pressure at the center (FK-C), but Product E, which is

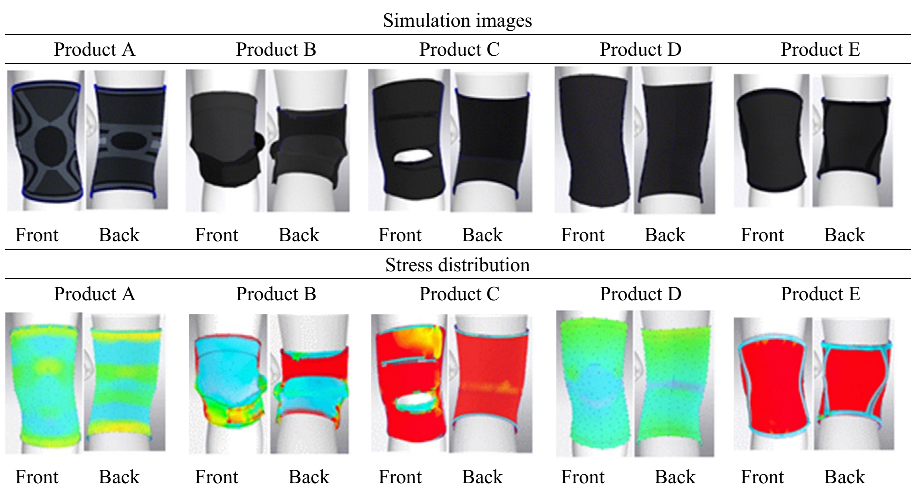


Fig. 3. 3D virtual clothing simulation images and stress distribution by product

made of the thickest material, had higher stress at the center than at the top or bottom, a feature that could put pressure on the wearer's knee. Products B and C offer relatively strong knee support due to higher stress at the lower knee (FK-LC) than at the center or the top. However, Products A and D showed higher stress at the upper knee (FK-UC). Regarding stress around the back of the knee, all the products had lower stress at the center (BK-C), except for Product B, for which there were no reported measurements. The lower center knee pit (BK-LC) and the inner knee pit (BK-LI) showed relatively high stress since the knee guard rests across the upper calf. Regarding the stress around the upper band, Products A, C, and D, which are long, showed high stress at the back center (UB-RC), and Products B and E, which are short, showed high stress around the front inner area (UB-FI).

Examining each product individually revealed that the high-stress points for Product A were the upper front knee area, the upper and lower areas of the knee pit, and the band circumference area (Fig. 3). Among them, the highest-stress points were the back center area of the upper band (UB-BC) and the back center area of the lower band (LB-BC); both had the same stress value of 60.21 kPa. The lowest-stress point was the center of the knee pit, with 22.54 kPa (Table 5). The band circumference area showed more stress than other points comprising the same knit structure because the area constituting the upper and lower band circumferences is smaller than for Product A than for the other products, so it is believed that the wearer's legs would be pressed and cinched more than for the other products. Product A also has a small knee circumference, but the stress there was not high because Product A comprises a knit structure that stretches well at the front knee, in the knee pit, and at the side center. However, the center of the upper front knee (FK-UC) had a stress value of 49.29 kPa, which is twice as much as the center area (FK-C); this is because it comprises low-stretch knit structure that adheres to the fleshy lower thigh.

Product B's design has different materials at different locations, and a large variation in stress levels was noted. The overlapping back area comprising laminated fabric had a high level of stress, and the front and back body plates made of thin and stretchable

Table 5 Stress values by measurement location

	FK-C	FK-UC	FK-LC	BK-C	BK-LC	BK-LI	UB-FC	UB-FI	UB-FO	UB-BC	LB-FC	LB-BC	LB-BI	BO-C
Product A	24.30	49.29	33.58	22.54	37.35	32.21	50.05	52.99	50.40	60.21	54.74	60.21	57.85	–
Product B	11.89	12.34	60.48	–	–	–	222.15	240.63	222.15	19.08	38.52	163.73	–	300.34
Product C	–	130.47	149.88	118.38	281.33	34,278	104.12	122.97	118.83	323.93	160.36	393.22	377.28	–
Product D	16.00	29.04	17.74	11.43	29.60	29.10	46.17	47.41	44.82	49.35	29.39	39.51	39.51	–
Product E	234.59	194.24	197.16	168.75	273.80	217.52	134.52	300.29	149.07	422.57	116.69	334.17	338.64	–

Unit of measurement for stress: kPa

jersey fabric had low levels of stress (Fig. 3). The center of the back cover (BO-C) had the highest stress at 300.34 kPa, and it is believed that the pressure was high because the cover comprising laminated fabric winds forward while pressing the back of the thigh and is secured under the knee with Velcro tape. Since this laminated fabric was also used at the inner ends of the circumference area above and below the front plate, it is believed that the stress was greater because the circumference area above and below the back plate adheres to the wearer's leg. The lower part of the front plate supporting below the knee with thick pile fabric showed high stress, and the stress on the lower center area of the knee (FK-LC) also increased as the narrow side extending from the back cover was tightened.

The highest-stress point in Product C showed a value of 393.22 kPa around the rear center area of the lower band (LB-BC). Product C's lower circumference is similar to that of other products. However, it is believed that the stress at the back center area (LB-BC) and inner parts (LB-BI) of the lower band increased because these comprise thick, punched fabric and the curvature at the back hem spans the calf muscles. Compared to Product E, which had overall high stress, Product C's upper band circumference area had lower stress. However, the stress on the lower band circumference area was higher in Product C. It is estimated that the upper circumference area of Product C is 5 cm larger than that of Product E, so Product C is roomier; however, the pull is greater because of the slightly longer length, and the lower circumference is smaller albeit by less than 1 cm (Table 2). Because Product C's back side is 1.5 cm longer than Product E's, it seems that the stress increased further, pressing on the upper part of the calf. The mesh fabric patched on the back plate is thinner but has less elasticity than typically found in jersey fabrics or knitwear, resulting in higher overall stress. Moreover, the stress levels around the inner (BK-LI) and rear center areas (UB-BC) of the upper band also increased, as these parts adhere to the backs of the calves and thighs (Table 5).

Product D had the lowest overall stress level among the analysis targets (Table 5). Specifically, the horizontal line around the front knee, the side, and the center of the rear area is composed of thin and highly stretchable knit structure, leading to low stress (Fig. 3). When the wearer's legs were bent, the folds on the side and back showed low stress, reducing the wearer's discomfort due to the product digging into the flesh and tightening. However, as a trade-off, it is likely that the product offers low support or protection due to failure to exert proper pressure around the knee. This product's upper band circumference area had relatively high stress, and the numerical values of all measurement points were higher compared to the lower band. The lower circumference is 5 cm larger than that of Product A, which has a similar design, so there is more roominess, which lowers the pressure. Although the front and back plates are made from the same knit structure, the stress at the lower front and back plates was lower than that at the upper and lower back plates. This may be due to the fact that Product D has an overall low level of force when adhering to the leg, leading to lower pressure on the shin, a less fleshy body part than the thighs and calves. The highest stress point was 49.35 kPa at the rear center of the upper band (UB-BC), but the highest value for this product was lower than those of other products.

Product E had the highest overall stress because it is made from the thickest and least stretchable laminated fabric (Fig. 3). This product has the largest difference in

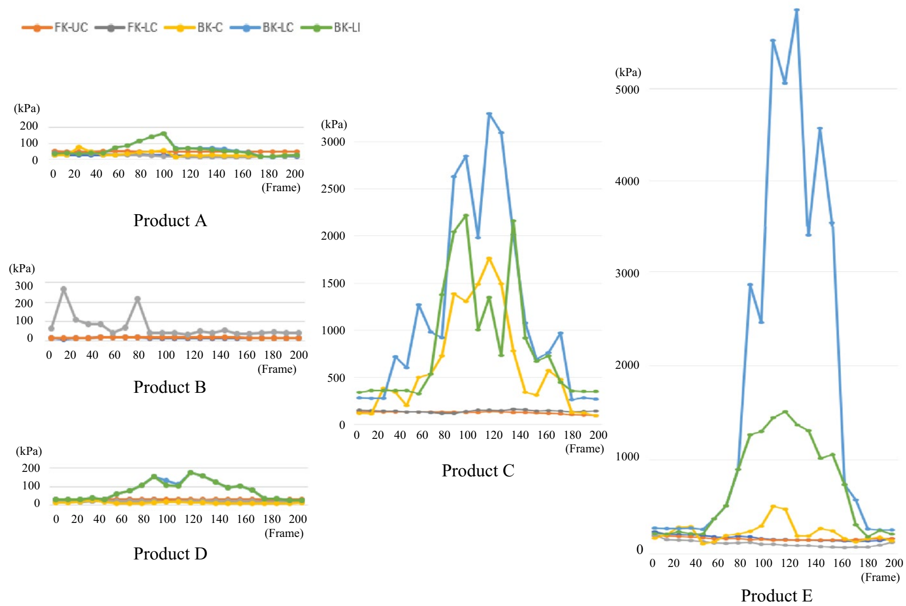


Fig. 4 Stress changes around the front and back of the knee by product

length between the front and the rear, and the upper circumferential line at the back is curved from the center. This facilitates increased mobility, but because the stress at the rear center of the upper band (UB-BC) was the highest at 422.57 kPa, discomfort for the wearer due to the tightness is to be expected (Table 5). Among the measurement positions on the front of the upper band, the stress at the front inner area (UB-FI) was 300.29 kPa, which is more than twice that of the other points; Product E differs from the other products in this regard. Furthermore, unlike the other products, the center of the front knee (FK-C) had stress. The overall stress was high due to the stiff, thick material, which is expected to cause wear discomfort as it increases the possibility of pressing the front knee harder while tightening around the legs. The lowest stress point was the lower band front center area (LB-FC), which showed a large numerical difference compared to the back center area (LB-BC) and the back inner area (LB-BI). These results are similar to those for Product C, which showed a large difference between its front and back sides.

Analysis of stress changes during simulated cycling

Figure 4 shows the results of comparing the stress changes at the front and back of the knee for each product during simulated cycling. Products C and E, which are made from laminated fabric, showed greater stress change in response to motion compared to the knitwear Products A and D, and the former also showed a larger difference in maximum values (Table 6). In all products, the stress difference from the starting point to the highest stress point was greater in the knee pit area than in the front knee area. The only exception was Product B, for which there was no knee pit measurement. High pressure on the knee is expected when the wearer's leg is bent. However, because of the flexible materials comprising the knee guards, the fabric stretches when the knee bends. CLO 3D measures the stress the avatar places on the product during wear but not that which

Table 6 Key figures reflecting stress changes around the front of the knee and the knee pit by product

	Measurement location	Starting-point stress	Peak		Lowest		Peak—starting-point stress	End-point stress
			Stress	Frame	Stress	Frame		
Product A	FK-C	24.28	29.25	70	14.38	170	4.97	16.27
	FK-UC	49.29	49.29	0	44.03	110	0.00	44.20
	FK-LC	33.58	34.38	10	12.41	140	0.80	18.5
	BK-C	22.54	74.15	20	13.12	100	51.61	22.89
	BK-LC	37.35	141.26	80	11.96	180	103.91	23.64
	BK-LI	32.21	141.26	80	14.54	180	109.05	23.64
Product B	FK-C	11.89	18.74	70	9.67	10	6.85	11.93
	FK-UC	12.34	18.89	110	11.00	10	6.55	11.73
	FK-LC	60.48	264.41	10	30.90	110	203.93	38.47
	BK-C	–	–	–	–	–	–	–
	BK-LC	–	–	–	–	–	–	–
	BK-LI	–	–	–	–	–	–	–
Product C	FK-C	–	–	–	–	–	–	–
	FK-UC	130.47	134.65	60	95.56	200	4.18	95.56
	FK-LC	149.88	159.75	130	118.83	70	9.87	143.65
	BK-C	118.38	1,765.57	110	95.15	200	1647.19	95.15
	BK-LC	281.33	3297.68	110	264.18	180	3016.35	270.40
	BK-LI	342.78	2220.34	90	342.78	0	1877.56	351.38
Product D	FK-C	16.00	27.42	60	13.73	180	11.42	15.02
	FK-UC	29.04	30.03	50	28.12	120	0.99	28.96
	FK-LC	17.74	21.93	30	16.47	170	4.19	20.62
	BK-C	11.43	24.64	30	4.80	180	13.21	13.23
	BK-LC	29.60	176.94	110	24.60	200	147.34	24.60
	BK-LI	29.10	176.94	110	23.96	190	147.84	24.19
Product E	FK-C	234.59	234.59	0	134.90	170	0.00	161.36
	FK-UC	194.24	194.24	0	148.67	150	0.00	163.25
	FK-LC	197.16	197.16	0	70.92	160	0.00	126.21
	BK-C	168.75	506.91	100	127.34	50	338.16	138.02
	BK-LC	273.80	5849.01	150	258.27	190	5575.21	258.56
	BK-LI	217.52	1513.56	110	183.69	180	1296.04	213.74

Unit of measurement for stress: kPa

the product places on the avatar. Therefore, it was difficult to determine the force applied to the skin on the front of the knee as the product extends.

At the points that showed large changes in stress in the knee pit area, values rose sharply whenever the wearer drastically bent their knee, and the stress levels fell once the knee was extended. The rear center (BK-C) was less stressed from the start than the lower center (BK-LC) and inner areas (BK-LI), and the increase in stress in this area was smaller when the knee was bent. This was probably because, at this position, most of the constituent materials are thin or stretchable, and it is believed that there is less force in terms of adherence to the inner knee pit area. The points with the highest stress increase in the knee pit area differed by product. Products A and D had the same stress level at the lower inner area (BK-LI) and the lower center (BK-LC) area, but Products C and E had higher stress at the lower center (BK-LC), and a very large change in the level of stress was observed there. In particular, the stress on the back and lower center (BK-LC) of Product E was overwhelmingly high at 5849.01 kPa, and the stress at the back center (BK-C) and lower inner (BK-LI) areas was lower compared to Product C. It is believed that this product becomes pressurized because the center of the lower part (BK-LC) presses into the upper part of the calf when the wearer's knee is bent, due to the thick fabric and the short rear length. Product D showed lower stress at these two points than Product A at the starting point. However, regarding the highest levels of stress, Product D's was higher than Product A's. It is highly likely that Product A comprises different knit structures with different elasticities at different points and that these stretch well with the wearer's movements.

Around the front knee, no significant change in response to motion was observed across all products except for Product B (Table 6). In Product B, the lower front knee (FK-LC) was the only part that showed a stress change, with the stress level rising sharply in Frame 10, immediately after the avatar began cycling, and then falling but rising again in Frame 70. As the stress level rose and fell, the changes were quite unstable. This was likely because the knee brace was pushed up and down as the wearer bent and began to straighten their legs and the upper and lower circumference areas tightened. During the cycling motion, the knee brace was not securely affixed to the wearer. For Product E, the stress around the front of the knee was the highest in Frame 0, but the drop in the stress level upon the cessation of motion was slightly larger than for other products (Table 6). This is because the material comprising Product E is thick and low in elasticity and it fit the avatar tight, so the overall stress was high. Consequently, however, the product was pulled up and down during movement, and the wearing position changed. For all products, the end-point stress value was lower than the starting-point stress value at most measurement points, and it is highly likely that the wearing position becomes slightly lower after the activity is completed.

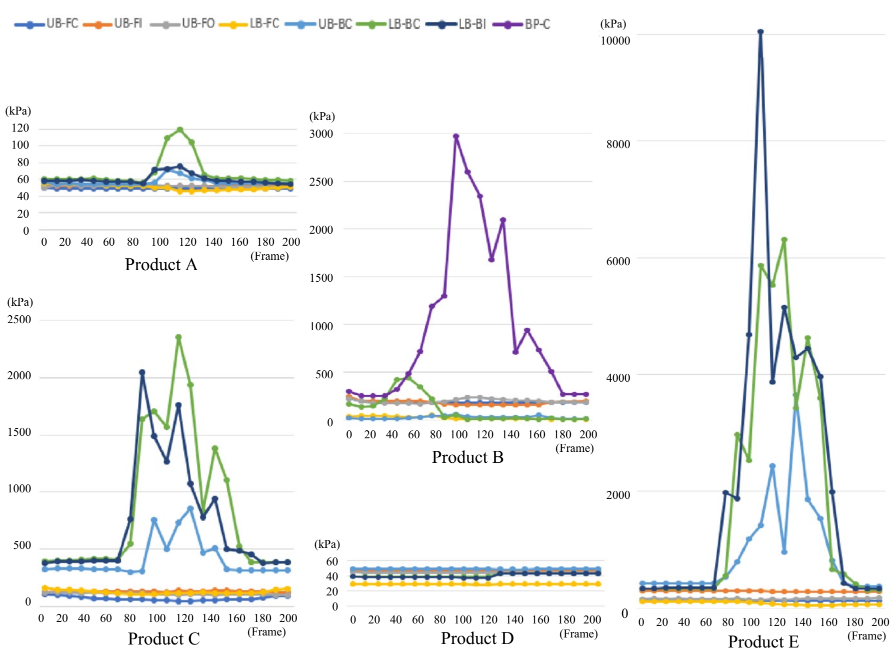


Fig. 5 Stress changes in the upper and lower band circumference areas by product

Figure 5 shows changes in stress around the upper and lower bands for each product during simulated cycling. Products C and E showed greater stress changes around the band areas than Products A and D, and Product B showed rapid stress changes at the center of the back overlay area (BO-C) only. For Product D, it was difficult to find meaningful stress changes because the same stress value was maintained for several frames at all positions; stress was low overall, and there was little change. For all the products,

Table 7 Key figures reflecting stress changes around the upper and lower circumference areas for each product

	Measurement location	Starting-point stress	Peak		Lowest		Peak-starting-point stress	End-point stress
			Stress	Frame	Stress	Frame		
Product A	UB-FC	50.05	50.05	0	49.02	20, 200	0.00	49.02
	UB-FI	52.99	52.99	0	51.69	60	0.00	51.92
	UB-FO	50.40	52.79	100	50.40	0	2.39	50.72
	UB-BC	57.41	71.71	100	54.06	70	14.30	55.29
	LB-FC	54.74	54.74	0	45.58	120	0.00	51.37
	LB-BC	60.21	119.41	110	56.33	80	59.20	58.46
	LB-BI	57.85	75.16	110	54.23	200	17.31	54.23
Product B	UB-FC	222.15	222.15	0	183.65	100	0.00	185.92
	UB-FI	240.63	240.63	0	159.34	100	0.00	197.44
	UB-FO	222.15	239.05	100	169.10	60	16.90	186.25
	UB-BC	19.08	45.07	70	12.04	20	25.99	12.82
	LB-FC	38.52	50.92	70	4.75	200	12.40	4.75
	LB-BC	163.73	438.72	50	5.22	180	274.99	9.98
	BO-C	300.34	2596.65	100	253.28	20	2296.31	266.97
Product C	UB-FC	104.12	104.12	0	45.76	110	0.00	92.52
	UB-FI	122.97	134.43	20	118.07	200	11.46	118.07
	UB-FO	118.83	121.85	10	96.59	200	3.02	96.59
	UB-BC	323.93	730.73	110	300.94	70	406.80	314.78
	LB-FC	160.36	160.36	0	101.27	80	0.00	151.95
	LB-BC	393.22	2359.60	110	380.98	170	1966.38	385.14
	LB-BI	377.28	2048.11	80	374.60	180	1670.83	381.79
Product D	UB-FC	46.17	46.17	0	45.67	Everything except 0	0.00	45.67
	UB-FI	47.41	47.41	0	46.09	Everything except 0	0.00	46.09
	UB-FO	44.82	44.82	0	44.43	70–160	0.00	44.44
	UB-BC	49.35	49.76	10	49.18	120–140	0.41	49.42
	LB-FC	29.39	29.39	0	28.71	100, 110	0.00	28.87
	LB-BC	39.51	42.81	120–180	39.39	10	3.30	42.80
	LB-BI	39.51	42.81	120–180	37.50	90	3.30	42.80
Product E	UB-FC	134.52	134.52	0	118.75	190	0.00	118.85
	UB-FI	300.29	300.29	0	281.73	110	0.00	287.30
	UB-FO	149.07	175.05	200	135.36	90	25.98	175.05
	UB-BC	422.57	3652.71	130	373.50	200	3230.14	373.50
	LB-FC	116.69	116.69	0	49.99	160	0	58.32
	LB-BC	334.17	6311.08	120	303.17	190	5976.91	307.46
	LB-BI	338.64	10,046.28	100	335.05	0	9707.64	338.65

Unit of measurement for stress: kPa

Table 8 Peak stress positions by product while stationary and in motion

	Ranking	Stationary		In motion				
		Peak location	Peak stress value	Peak location	Peak stress	Peak frame	Difference in peak-lowest stress	End-point stress
Product A	1	UB-BC	60.21	BK-LC	162.20	90	150.24	23.64
	2	LB-BC	60.21	BK-LI	162.20	90	147.66	23.64
	3	LB-BI	57.85	LB-BC	119.41	110	63.08	58.46
Product B	1	BP-C	300.34	BP-C	2970.90	90	2,717.62	266.97
	2	UB-FI	240.63	LB-BC	438.72	50	433.50	9.98
	3	UB-FO UB-FC	222.15	FK-LC	264.41	10	234.32	38.47
Product C	1	LB-BC	393.22	BK-LC	3297.68	110	3033.50	270.40
	2	LB-BI	377.28	LB-BC	2359.60	110	1974.46	385.14
	3	BK-LI	34,278	BK-LI	2220.34	90	1877.56	351.38
Product D	1	UB-BC	49.35	BK-LI	176.94	110	152.98	24.19
	2	UB-FI	47.41	BK-LC	176.94	110	152.34	24.60
	3	UB-FC	46.17	UB-BC	49.76	10	0.58	49.42
Product E	1	UB-BC	422.57	LB-BI	10,046.28	100	9711.23	338.65
	2	LB-BI	338.64	LB-BC	6311.08	120	6007.91	307.46
	3	LB-BC	334.17	BK-LC	5849.49	120	5591.22	258.56

Unit of measurement for stress: kPa

the front of the band showed few stress changes, so there was little numerical difference between the starting point and the highest point (Table 7). Most of the stress changes that occurred at the back of the band showed the highest stress level at 90-degree knee flexion, which is the most drastic bent-knee angle, but the stress level fell again when the wearer extended their knee.

On the back panel, the lower band showed greater stress change than the upper band. The position where the most rapid stress changes occurred was the back center of the lower band (LB-BC) in Products A, B, and C and the back inner area (LB-BI) in Product E. The stress at the back center (LB-BC) and back inner (LB-BI) areas of the lower band of Product E was lower than the stress at the same positions on Product C at the starting point; however, stress here was very high at the peak point. Specifically, the stress at the back inner area (LB-BI) was 9707.64 kPa, nearly six times higher than the corresponding value for Product C. This is believed to have occurred because the product was pushed deeper into the calf flesh during knee flexion, as evidenced by the stress change at the lower center area (BK-LC). Product C had the highest stress at the starting point, and then stress increased by more than eight times in Frame 100 where the center of the back overlay (BO-C) bent maximally along with the knee; it is believed that the thick, low-stretch laminated fabric comprising the overlay pressed hard on the back of the thigh as the wearer's legs bent.

Table 8 shows the results of comparing the high-stress positions across products while the avatar was stationary and the positions where the stress level increased and showed the highest values during motion. Except for the area around the knee pit, which folds when the wearer's leg is bent, it was found that the upper band circumference area, which showed high stress while stationary, was less likely to accommodate motion.

However, stress levels rose at the back of the lower band during motion. The product with the largest change in stress due to the commencement of motion was Product E, and the difference between the lowest and highest values recorded at the back inner area of the lower band (LB-BI) was 9711.23 kPa, over three times the corresponding value for Product C. When stationary, the stress at this point was not the highest, but this point was found to be the most affected by the commencement of motion. The second highest stress points in Product E were the back center of the lower band (LB-BC) and the lower center of the knee pit (BK-LC), and, for these two positions, the stress difference between the highest and lowest points was also significantly higher compared to Product C.

Products B and C had the highest peak stress, at around 3000 kPa, when motion began, but for Product C, the lower center of the knee pit (BK-LC) had the highest stress and the largest difference with respect to the lowest point, at 3033.50 kPa. The next highest stress point at rest was the back center of the lower band (LB-BC), but the stress level at this point did not rise higher than that at the lower center knee pit when motion began. Although the lower center (BK-LC) and inner (BK-LI) parts of the knee pit sit adjacent to each other above the wearer's calf, a difference in stress change magnitude was noted before and after motion. The stress at the center was lower than the inner part at rest, but it increased to the highest level during motion and was about 1.5 times higher than the stress at the inner part, demonstrating that the center was more affected by the cycling movement.

Product B had the highest stress while stationary, and the stress at the center of the overlay (BO-C) was overwhelmingly high when motion began, resulting in the largest change in stress level. Next, the center of the back of the lower band (LB-BC) and the center of the lower knee (FK-LC), which had the next highest stress values, were not under high stress while the wearer was stationary, and the degree to which the stress increased was also larger compared to the back overlay. The highest value at these two points was shown when the wearer's knee was bent at a 90-degree angle in Frames 50 and 10. The lower band had very low stress at the end point, showing an unstable change pattern. The front of Product B's upper band was stressed at rest, but the change observed at these points was not significant when motion commenced.

Products A and D, which had low overall stress at rest, showed less change than the other products even after motion had begun. Both products were greatly influenced by the commencement of motion on the part of the wearer at the lower area of the knee pit, and the next highest-stressed positions were behind the lower band in Product A and behind the upper band in Product D; notably, these products have similar materials and designs. At these positions, stress at rest was higher than that at the back, but when motion began, the stress increase was lower. Additionally, the back center of Product A's upper band (UB-BC) was the most stressed at rest, but no significant change was observed when the wearer set into motion.

Discussion

This study examined pressure distribution and changes across various locations on different knee braces as part of a functional design analysis focusing on clothing pressure for knee brace products that are currently widely used for cycling. The result of this study found that the pressure exerted by knee braces was largely dependent on the material type and the detailed size of each location. Differences in material, such as the placement of different fabrics or structures in different areas of the knee brace, affected the clothing pressure distribution and its change pattern. Different adjustment methods and additional details also affected clothing pressure by location.

Because the thickness and elasticity of the materials comprising the various knee braces differed by type of material, the overall clothing pressure exerted by the laminated fabric comprising Products C and E, which are thick with relatively low elasticity, was higher compared to the knit material comprising the other products such as A and D. Furthermore, a large change in clothing pressure was observed when the wearer set into motion. Hence, these knee braces are likely to cause inconvenience when worn for prolonged periods while cycling.

According to a previous study by Baek et al. (2022) on the clothing pressure of knee guards, skin pressure around the knees and calves under the knee guards were less manifested during dynamic motions (e.g., kicking, jumping) when compared to static positions (e.g., sitting or standing), and the cause was presumed to be their impact-absorptive construction and elastic materials. However, in this study, the clothing pressure mostly changed higher during cycling motions than in static positions. Since the cycling motions was a continuous movement with rotating legs in a sitting position, the condition could be different from the movement in which a high impact was instantaneously imposed, such as when landing after running or jumping. And it is considered that the change in clothing pressure was greater in products made of thick and less elastic materials due to less pressure dispersion. Therefore, among all the analyzed products, Product E is made of the thickest and hardest material and thus had the highest clothing pressure overall; hence, it is expected that wearers will find it relatively difficult to bend their knee because high pressure is applied to the center of the front of the knee. Even with thick materials such as that used in Product E, unnecessary pressure can be reduced depending on how the knee brace is adjusted when in use as well as on the shape of the outline design. Product C, which consists of punched laminated fabric, was also found to exert high clothing pressure, but when wrapped around the leg, this knee brace can be relaxed as needed, and the exposed knee design reduces the pressure. However, because the front plate is thick with two layers in the form of a wrap that overlaps the top and bottom, the inner circumference decreases when it is opened and worn in place, causing it to strongly adhere to the leg, which eliminates the effect of reducing the overall pressure.

Depending on the design of a given knee brace, the pressure can be adjusted at a particular location through the use of a material that would produce that effect. For instance, Product B's front and rear body plates are made of thin and stretchable jersey, which was observed to reduce the clothing pressure and prevent tugging on the knee during leg flexion. However, because laminated fabric was used for this product's inner and overlapping parts, the thick overlapping layer presses down on the lower thigh and winds forward to be fixed under the knee, which applies more pressure and further tightens the upper and lower circumference areas. Consequently, the back plate of the thin material folds and clumps together and will likely cause inconvenience because there is a high possibility that it will fall out of the original wearing position during cycling.

Clothing pressure varies in the degree of positive effect on the body depending on the use of clothing, and excessively low clothing pressure can negatively affect the comfort of the wearer (Kim & Park, 2022). It is important that knee brace designs reduce unnecessary clothing pressure, but it is also important to increase knee protection and support as reducing discomfort by applying appropriate pressure at strategic positions where pressure is necessary. For instance, appropriate force needs to be applied to the lower part of the knee, but it is important that the center and upper part of the knee do not come under excessive pressure. Product B provides knee support through the exertion of high clothing pressure due to the thick pile fabric at the bottom of the front knee; moreover, wearers can customize the closing position of the covering portion, which can be wound forward and fixed with Velcro tape, so that more pressure will be applied as needed. Product C also offers higher clothing pressure under the knee compared to any other point, and because it is a wrap closure with an open center, the Velcro tape at the bottom is fixed further inward to add pressure under the knee. On the other hand, Product D was judged to have difficulty supporting the knee effectively because fabric that stretches well throughout the knee was used, resulting in low clothing pressure around the knee and even lower pressure at the bottom of the knee.

Length and circumference were also found to affect clothing pressure. Product B is expected to cause wearers a relatively high degree of discomfort due to the garment tightening and rolling up; this is likely to happen because the upper and lower circumference are small, and thick fabric was used in the inner parts. On the other hand, Product D is long with a large circumference at the bottom, so it lacks the strength to adhere closely to the bottom of the wearer's knee. A design where the circumference at both ends is curved due to the length difference between the front and back as well as the overall length has the effect of increasing the clothing pressure, as knee braces are intended to be placed on the lower thigh or upper calf. Product C, for example, exerts pressure at the back of the lower band as it digs into the calf with a line with a gradually shorter back hem. Product E has the largest length difference between the front and the back, but the back hemline is more curved and goes higher above the calf, so the clothing pressure around the lower circumference is not very high; pressure is higher around the front and the upper circumference under the thigh. This was consistent with the results of study of Lee and Do (2023) on leggings, in which the clothing pressure was influenced more by circumference than length, and products with small circumference showed relatively high clothing pressure at each location.

Conclusions

This study provided reference data for design development of cycling knee brace by examining clothing pressure of different design products. Based on the results of this study, the thickness and elasticity of the material should be carefully selected first in the development of knee brace design. Overly thick and less elastic materials need to be reconsidered in knee braces design in order to avoid exerting continuous clothing pressure. Also, designers should consider an appropriate length and circumference in order to improve the functionality and fit of cycling knee brace products in the material selection process. In knit products, the thickness of the fabric could be increased or structure with relatively low elasticity could be used to increase support at the lower knee where there should be imposed appropriate pressure. Textile products can incorporate additional details and options to cover the lower knee. However, these design elements should be applied with respect to the product's structure and size and with consideration to accommodating flexion of the body parts with which the product comes into contact during use. In particular, it is necessary to check whether the length and circumference are appropriate considering the movements involved in cycling. Furthermore, detailed inspection is required because clothing pressure changes may vary even between adjacent positions on the knee brace. Finally, designs should be such that there is no discomfort for wearers at the front and rear edges of the product; this can be achieved by duly considering the difference in body volume between the thigh and the calf depending on a range of cycling movements. It is also important to ensure that the product remains stable; that is, it should not move from the original wearing position during cycling activities.

This study tried alternative research methods to examine the possibility of replacing actual experimental measurements, with a focus on analyzing the clothing pressure of functional clothing products using a 3D virtual clothing program. This study is meaningful in that it provides basic data on research methods that can be attempted relatively easily in sports clothing design by tracking changes in clothing pressure across motion frames during simulated cycling. However, since stress as defined in the program used in this study was calculated as the effect of avatars on clothing, it was difficult to make a numerical comparison with previous studies that measured the pressure value applied to the body by clothing pressing the skin. Therefore, there was a limit to identifying the standard value of clothing pressure (Denton, 1972; Johansson et al., 2002; Makabe et al., 1991) presented in order not to cause blood flow disorders or pressure discomfort in pressed clothing in this study, and muscle volume deformation and skin surface friction during wear and in motion could not be reflected. It is necessary to verify the accuracy of the construction and material of the product reproduced in the 3D virtual clothing program with the actual products, and comparative verification through follow-up studies will be needed because wearers' degree of pain or discomfort due to clothing pressure was not compared with actual wearing experience. Additionally, this study proposes additional research that considers the difference between simulated cycling motion and actual cycling behavior.

Acknowledgements
Not applicable.

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Funding
This work was supported by Ministry of Education of the Republic of Korea and the National Research Foundation of Korea (NRF-2020R1A2C2004502, NRF-20221A5A805561812).

Availability of data and materials
The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests
The authors declare that they have no competing interests.

Received: 9 March 2023 Accepted: 21 July 2023
Published online: 18 September 2023

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