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Effects of wearing knee-guards on skin pressure and skin blood flow during dynamic motions

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Abstract
The purpose of the present study was to explore the effects of wearing knee guards on skin blood flow and skin pressure during dynamic soccer motions. Twenty-one male subjects participated in the following two experimental conditions: wearing knee guards (KG) and no knee guards (Control). Subjects performed several consecutive soccer motions along with a standing position between each motion. Skin blood flow and skin pressure on the thigh, knee, and calf were monitored. The results showed that skin pressure had the greatest value in a sitting position for both the KG condition and Control, but the smallest during instep kicking and switching directions ($P < 0.001$). The rear calf had the greatest skin pressure for the KG condition ($P < 0.001$), while the side knee showed the greatest for the Control ($P < 0.001$). Normalized skin blood flow based on values from their standing position was the greatest during the jump motion among the various soccer motions. Interestingly, skin blood flow decreased by wearing the knee guards on the front thigh and calf ($r = -0.859$; $r = -0.835$; $P < 0.001$), while the blood flow increased on the side knee ($r = 0.295$, $P < 0.001$). Subjects felt greater skin pressure sensation during the jump motion and switching directions than other soccer positions/motions ($P < 0.001$). These results indicate that the knee guards result in relatively lighter pressure for dynamic motions (e.g., kick, switching directions, or jump) than for static positions (e.g., sitting or standing), and the skin blood flows for the thigh, knee, and calf are redistributed by wearing the knee guards, especially during jumping.

Keywords: Knee-guard, Soccer movement, Skin pressure, Skin blood flow rate, Dynamic motions

Introduction
Over the past 50 years, various types of pressure or protective garments have been worn to treat chronic venous disorders (CVD) (Fletcher et al., 2013), treat burns (Macintyre & Baird, 2006), promote body shaping (Chan & Fan, 2002; Jeong et al., 2006), increase swimming performance (Kramer et al., 2001), prevent of athlete injuries or promote their recovery (Beliard et al., 2015; Ghai et al., 2018; Hong & Lee, 2020; Otten et al., 2019), improve activity (Gandevia et al., 2006), and reduce muscle fatigue (Miyamoto et al., 2011; Van Tiggelen et al., 2008). In particular, applying pressure to the lower legs has been used to improve leg performance and prevent

leg swelling. In terms of performance, Stolk et al. (2004) reported that the increased performance of medical compression hosiery during walking, while most related studies reported results in supine positions (Mayrovitz & Larsen, 1997; Mayrovitz & Sims, 2003). Further, results concerning skin blood flow while wearing compression garments were anecdotally reported for the toes (Mayrovitz, 1998), the foot (Mayrovitz, 1996), and the calf (Ashton, 1975).

In practice, the most extensively used pressure garments are knee guards. Oh and Oh (2021) reported that older people wear knee guards to reduce pain and young people wear knee guards to reduce impacts during their sports activities. In particular, the most frequently injured body region of soccer athletes was the knee (Forbes et al., 2013), showing about 15–24% of all injuries during soccer games and training (Kim & Kim, 2004). And the 44% of the knee injuries were observed from the anterior cruciate ligament (Thacker et al., 1999). To prevent knee injuries, soccer athletes wear knee guards during games and training (Lim et al., 2012). The knee injuries often occurred while rebounding or landing from a jump rather than from body contact with other athletes (Daniel et al., 1994). Because soccer players often experience knee injuries when the knee flexor and extensors are not coordinated (Choi, 2019), wearing knee guards could help by absorbing shock around the knee when landing a jump (Cho & Kim, 2015). Knee guards prevent abnormal moving of knee muscles (DeVita et al., 1996), reduce muscle activity around the thighs (Ramsey et al., 2003), prevent overloading of the anterior cruciate ligament (Flemming et al., 2000), and improve overall competitive performance (Rebel & Paessler, 2001). Cuff pressure, such as a knee-guard, limits the excessive skin blood flow rates and increase exercise stability as proprioception changes caused by skin pressure are advantageous in controlling exercise posture (Eysel-Gosepath et al., 2016). However, a series of studies on knee guards showed little benefit. For example, wearing knee guards did not reduce knee injuries (Birmingham et al., 1998, 2000; Herrington et al., 2005), thigh compression garments did not effectively promote movement of knee joints (Negyesi et al., 2018), wearing compression garments had no effect on skin pressure during exercise (Beliard et al., 2015), and positive effects of wearing compression garments could be a placebo (Mothes et al., 2017).

Such inconsistencies concerning the beneficial effects of knee guards might be attributable to the fact that compression garments with new materials and new construction designs have been developed. The variety of new knee guards with new materials and designs makes every new generation of knee guards obsolete rather quickly. Thus elucidating the physiological role of wearing knee guards and physiological mechanisms in related performance improvements, rather than comparing new knee guards with old knee guards was the goal of the present study. We analyzed skin pressure and skin microcirculation while wearing knee guards and explored the changes in physiological responses from dynamic soccer motions. The hypotheses of the present study were as follows. First, wearing knee guards would induce higher skin pressures for sitting posture compared to standing or kicking motions. Second, skin blood flow in the legs would show smaller variations among various postures/motions while wearing knee guards than for no knee guards.

Methods

Subjects and experimental clothing

Twenty-one healthy male college soccer athletes (22.4 ± 1.7 y in age, 174.3 ± 2.7 cm in height, 70.9 ± 10.4 kg in weight) participated in the two experimental conditions: with knee-guard (KG) and without knee-guard (Control). All subjects were informed about the experiment and signed informed consent prior to participation. The Institutional Review Board of Seoul National University approved the present study (IRB#2008/001-007). The knee guards (Polyamid 62%/Elastan 15%/Polyester 12%/Merino 11%, Silicon 100% pad for front knee) in the present study were a major ligament protective guard (Genu-train 8 generation, Baufeint, Germany; total length 33 ± 2 cm) (Fig. 1a). Subjects wore short sleeve T-shirts (Polyester 100%), short pants (Polyester 100%), knee-length nonslip socks (Nylon 99%/Polyurantan 1%), and running shoes (Fig. 1d, e). The knee guards covered all measurement sensors.

Measurements

Laser Doppler skin blood flow (LDF) was continuously measured on the four body sites (the front calf, middle knee, side calf, and front thigh) on the dominant leg using an LDF device (Moors VMX-LDF2, Moors Inc., UK) (Fig. 1b, c). Skin pressures under the knee guards were continuously measured every 1 s on the eight sites on the dominant leg (Fig. 1b, c) using a pressure device with air-cell pressure sensors (Ø-20 air pack sensor, Sartorius, Japan). For the control (without the knee guard), skin pressures were measured on the five skin sites (the middle knee, side knee, front calf, side calf, and rear calf) (Fig. 1b, c). The skin pressure sensors for the control condition were placed below the knee-length socks. Skin pressure sensation on the knee regions was recorded using a 7-point scale (− 3 very loose, − 2 loose, − 1 a little loose, 0 neither, 1 a little tight, 2 tight, 3 very tight). For the static postures (standing and sitting), subjects reported their knee skin pressure sensation at 30th s of 60 s, while for active

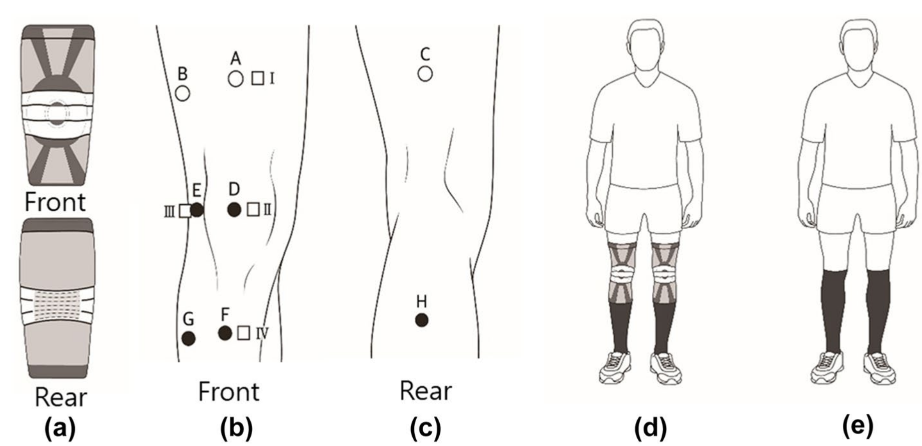

Fig. 1 Front and rear side of the knee guard (**a**), eight regions of skin pressure measurements for the knee-guard condition (A to H) (**b**, **c**) and five regions for the control condition (D to H) (filled circle: covered by knee socks, open circle: not covered by the knee socks) (**b**, **c**), and four regions of SBF (skin blood flow) measurements (I to IV) (**b**), the KG condition (**d**), and the Control condition (**e**)

motions (a knee-moving, long kick, instep kick, and jumping) skin pressure sensation was recorded as soon as each action was completed.

Experimental conditions and procedures

All trials were conducted at an air temperature of 24 °C with a relative humidity of 50%, and air velocity of below 0.15 m s^{-1} in a climate chamber. All subjects participated in the two experimental conditions: with/without knee-guard (Fig. 1d, e) at a random order to avoid any possible order effect. When subjects arrived at a preparation room, they changed into experimental clothing (Fig. 1d). Then they entered the climate chamber and sat on a chair. Sensors to measure skin pressures and skin blood flow were attached to the designated sites (Fig. 1b, c). A trial consisted of 11 consecutive postures/motions for 9.5 min excluding a 10-min stabilization: 10-min rest on a chair, standing (60 s), sitting (60 s), standing (60 s), moving the knee left and right at the 45° knee angle (60 s), standing (60 s), long kicking with a dominant leg (30 s), standing (60 s), instep kicking a dominant leg (30 s), standing (60 s), jump (30 s), and standing (60 s) (Fig. 2).

Data analysis

The skin blood flow rate was measured every 0.1 s and averaged into 1 s, then normalized based on the value of the initial 60 s of the standing posture. When averaging, values from the first 3 s and the last 3 s were excluded in order to minimise the influence of changing from a posture to another posture. The difference between the two conditions was tested by a Paired T-test or Wilcoxon signed-rank test. The difference among the 11 motions was tested by Duncan test. In order to test the time and posture effects, a repeated measure ANOVA was used. Statistical significance was set at $P < 0.05$. All data were presented as mean ± standard error (SE).

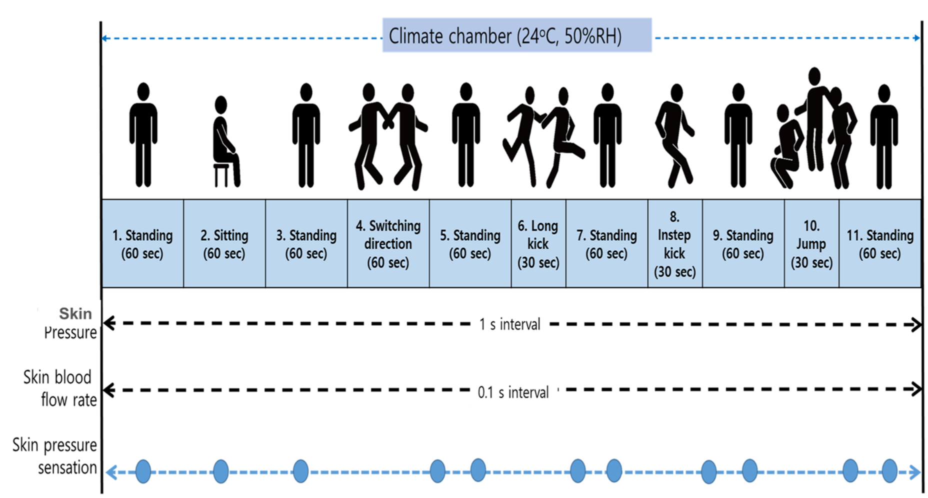

Fig. 2 The experimental protocol and measurement items in the present study

Results

Skin pressure

Skin pressure on the eight skin sites (21 subjects) while wearing the knee guards was 18.3 ± 2.0 mmHg (minimum 0.2–maximum 95.4 mmHg), while the average value for the control without any knee guards but wearing the knee socks was 5.9 ± 1.0 mmHg (minimum 0.04–maximum 56.7 mmHg) (Table 1). Among various postures and dynamic motions, the greatest skin pressure was found in the sitting posture, while the smallest skin pressure was found in dynamic motions, such as kicking and switching direction (Table 1, $P < 0.001$). Among the various body regions, for the knee guard condition, skin pressure was the highest on the rear calf (25.0 ± 1.0 mmHg) and front calf (23.7 ± 1.7), followed by rear thigh (21.5 ± 1.0) > side calf (20.7 ± 1.5) > side knee (17.4 ± 3.3) > middle knee (14.6 ± 1.5) > side thigh (14.4 ± 1.0) > front thigh (9.2 ± 0.8) ($P < 0.001$). For the control condition, the skin pressure was highest on the side knee, followed by the middle knee (9.1 ± 1.6 mmHg) > back calf (7.7 ± 0.8) > front calf (4.2 ± 0.6) > side calf (3.7 ± 0.4) ($P = 0.001$, Fig. 3).

Normalized skin blood flow rate

Normalized skin blood flow (%LDF) showed the greatest value for the jump motion (190 ± 20% in the KG condition, and 226 ± 24% in the control) (Table 2, Fig. 4). The skin blood flow (%LDF) on the thigh and calf was smaller for the KG condition than for the control, but the knee showed greater values for the KG condition than for the Control (Table 2, Fig. 4). Regional comparisons were not conducted because the values were normalized based on the 1st standing value of each body region.

Table 1 Skin pressure averaged from the knee, calf, and thigh for the knee guard condition (KG) and the control while the 11 consecutive motions were conducted (unit: mmHg)

Posture/motions	Knee guard condition (8 regions)	Control (5 regions)	*P-value**
1. Standing	18.5 ± 0.7^{ab}	5.0 ± 0.3^{ab}	*< 0.001*
2. Sitting	20.5 ± 0.8^{b}	9.9 ± 0.7^{e}	*< 0.001*
3. Standing	18.6 ± 0.7^{ab}	4.9 ± 0.3^{ab}	*< 0.001*
4. Switching the direction	17.0 ± 0.8^{a}	7.1 ± 0.4^{d}	*< 0.001*
5. Standing	18.8 ± 0.8^{ab}	5.0 ± 0.2^{ab}	*< 0.001*
6. Long kicking	17.8 ± 1.0^{a}	6.0 ± 0.3^{bc}	*< 0.001*
7. Standing	18.7 ± 0.8^{ab}	5.0 ± 0.3^{ab}	*< 0.001*
8. Instep kicking	16.8 ± 0.8^{a}	5.0 ± 0.3^{ab}	*< 0.001*
9. Standing	18.6 ± 0.8^{ab}	5.5 ± 0.3^{ab}	*< 0.001*
10. Jumping	18.0 ± 0.8^{ab}	6.7 ± 0.4^{cd}	*< 0.001*
11. Standing	18.5 ± 0.8^{ab}	4.7 ± 0.3^{a}	*< 0.001*
Total average	18.3 ± 0.2	5.9 ± 0.1	*< 0.001*
*P-value***	*0.141*	*< 0.001*	

N = 21; *Differences between two conditions; **Differences between the 11 postures. The upper cases of a,b,c,d,e represent statistically identified groups classified by Duncan test among the 11 motions. Data are expressed as mean ± SE

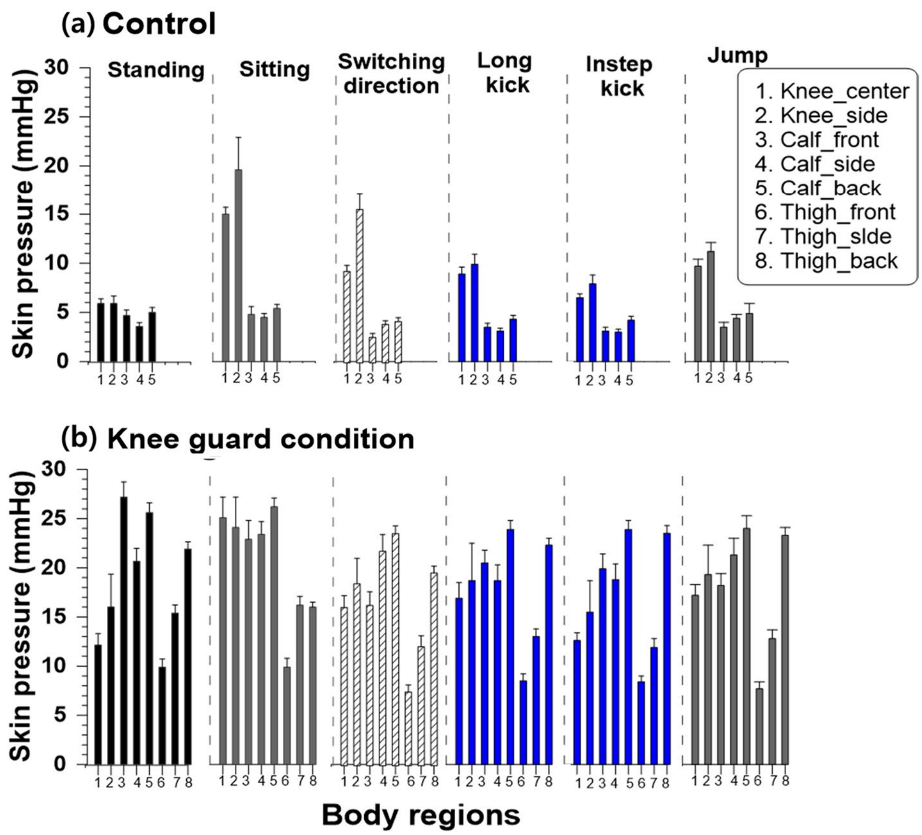

Fig. 3 Body regional skin pressure for the Control (**a**) and the knee guard condition (**b**). Data are expressed as mean ± SE. The data of the standing posture were averaged from the 1st, 3rd, 5th, 7th, 9th, and 11th standing periods

Correlation between skin pressure and normalized skin blood flow rate

Negative relationships between skin pressure and skin blood flow on both front thigh and front calf were found ($P < 0.001$, Fig. 5a, d), whereas positive relationships on the side knee were found ($P < 0.001$, Fig. 5c).

Skin pressure sensation

Skin pressure sensation for the knee guard condition ranged from 'a little tight (score 1)' to 'tight (2)', while skin pressure for the control ranged from 'not either (0)' to 'a little tight (1)' (Table 2). Subjects felt more skin pressures for jumping and switching directions when compared to those during sitting or standing positions (Table 3).

Discussion

Our first and second hypotheses were proved: (1) wearing knee guards induced higher skin pressures in a sitting posture compared to standing or kicking motions, and (2) skin blood flow showed smaller variations among various postures/motions while wearing the knee guards than for no knee guards. We discuss more about the underlying mechanism of the observed findings in terms of physiology, psychology and knee guard design.

Table 2 Skin blood flow by body region and body posture/motions for the knee guard condition (KG) and the control condition (unit: %)

	Knee guard condition				**Mean**	**Control condition**				**Mean**
	Front thigh	**Middle knee**	**Side knee**	**Front calf**		**Front thigh**	**Middle knee**	**Side knee**	**Front calf**	
1. Standing	0	0	0	0	0	0	0	0	0	0
2. Sitting	5 ± 0^{a}	-37 ± 1^{a}	7 ± 0^{a}	-6 ± 0^{a}	-8 ± 1^{a}	-1 ± 0^{a}	-53 ± 2^{a}	-2 ± 0^{a}	-1 ± 0^{a}	-14 ± 2^{a}
4. Switching directions	72 ± 1^{d}	158 ± 2^{c}	157 ± 2^{d}	106 ± 2^{c}	123 ± 3^{c}	134 ± 1^{c}	161 ± 2^{bc}	109 ± 1^{c}	140 ± 2^{c}	136 ± 2^{c}
6. Long kicking	68 ± 2^{c}	158 ± 3^{c}	146 ± 3^{c}	114 ± 2^{d}	121 ± 4^{c}	182 ± 19^{d}	166 ± 4^{c}	122 ± 2^{d}	148 ± 2^{d}	155 ± 3^{d}
8. Instep kicking	54 ± 1^{b}	147 ± 3^{b}	113 ± 2^{b}	80 ± 2^{b}	98 ± 4^{b}	114 ± 1^{b}	157 ± 3^{b}	103 ± 3^{b}	101 ± 1^{b}	119 ± 3^{b}
10. Jumping	114 ± 3^{e}	207 ± 6^{d}	198 ± 5^{e}	152 ± 5^{e}	168 ± 4^{d}	248 ± 5^{e}	204 ± 4^{d}	181 ± 3^{e}	221 ± 3^{e}	213 ± 3^{e}
Total	55 ± 3	105 ± 7	110 ± 5	76 ± 4	87 ± 3	113 ± 6	103 ± 8	86 ± 5	105 ± 6	102 ± 3
P-value	*< 0.001*	*< 0.001*	*< 0.001*	*< 0.001*	*< 0.001*	*< 0.001*	*< 0.001*	*< 0.001*	*< 0.001*	*< 0.001*

The upper cases of a,b,c,d,e represent statistically identified groups classified by Duncan test among the motions. Data are expressed as mean ± SE

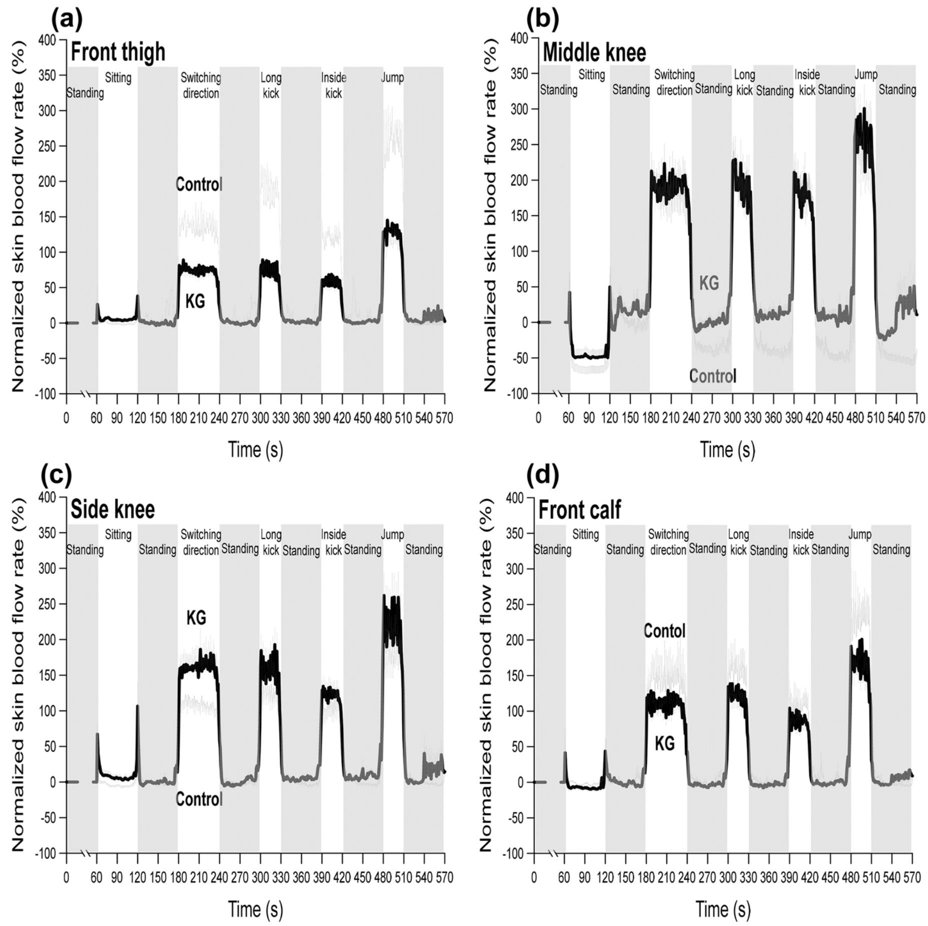

Fig. 4 Time courses of normalized skin blood flow rate (%) by soccer posture and motions while wearing the knee guard condition (KG) and the control condition on the front thigh (**a**), middle knee (**b**), side knee (**c**), and front calf (**d**)

Increased skin pressure by wearing knee guards: static positions vs. dynamic motions

It is no wonder that wearing knee guards resulted in increased skin pressure around the knees and calves, but the novel finding of the present study was that such increases were less manifested during dynamic motions (e.g., kicking, switching directions, or jumping) rather than in static positions (e.g., sitting or standing). Why was the increase in skin pressure alleviated while doing dynamic motions? Simply put, our results showed that skin pressure under the knee guards was more effectively dispersed over during the dynamic soccer motions, which may be due to their impact-absorptive construction and elastic materials. The knee guards in the present study consisted of elasticated pads ensuring effective distribution of knee joint power along with multiple types of fibers (Polyamide, Styrene–Ethylene–Butylene–Styrene Block Copolymer, Elastane, Polyurethane, Cotton, Polyolefine, and Polyethylene). Doan et al. (2003) evaluated the effects of custom-fit compression shorts on the athletic performance of track athletes. They found that muscle oscillation decreased during vertical jump landing and the impact force was reduced by 27% while wearing the compression shorts when compared with American football pants alone.

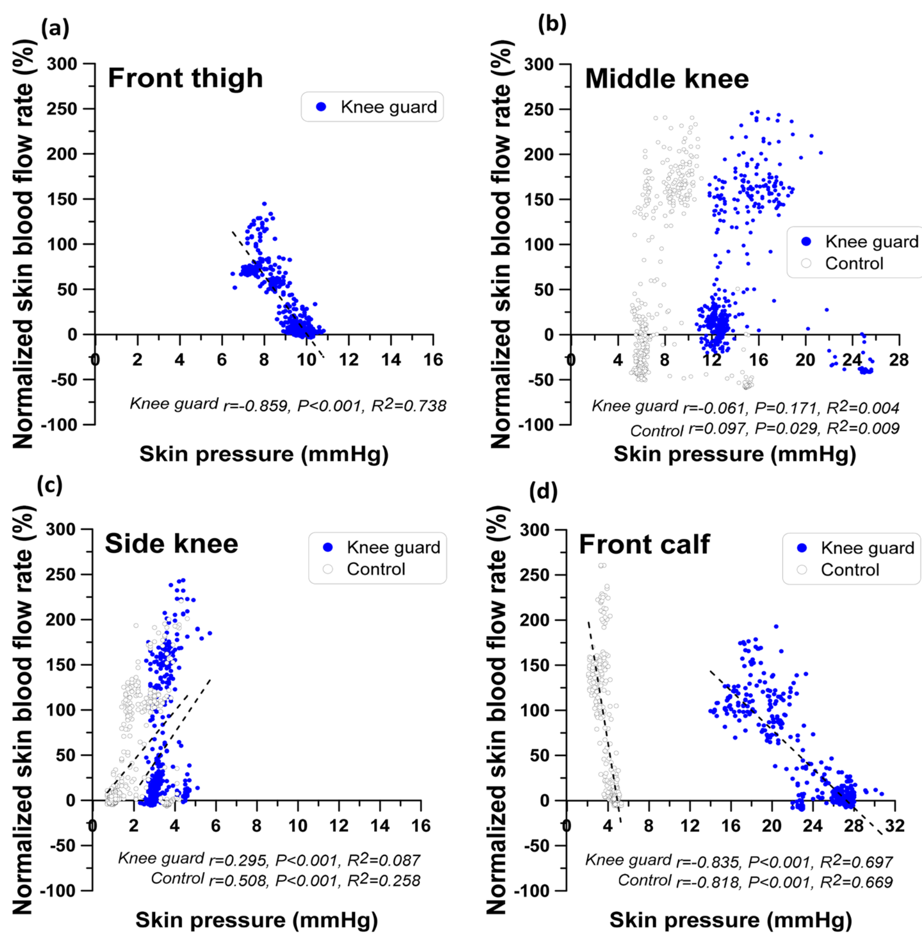

Fig. 5 Relationships between skin pressure and normalized skin blood flow for the control and knee guard condition (KG) on the front thigh (**a**), middle knee (**b**), side knee (**c**), and front calf (**d**)

Table 3 Skin pressure distribution by measured points and posture with and without knee-supports

Posture/motion	Knee guard condition	Control	P value
Standing 1st	1.4 ± 0.7^{ab}	0.5 ± 0.6^{ab}	< 0.001
Sitting	1.2 ± 0.8^{b}	0.1 ± 0.5^{b}	< 0.001
Standing 2nd	1.3 ± 0.7^{b}	0.5 ± 0.6^{ab}	0.001
Switching directions	1.6 ± 0.9^{a}	0.8 ± 0.6^{a}	0.001
Standing 3rd	1.3 ± 0.7^{b}	0.5 ± 0.5^{ab}	< 0.001
Long kicking	1.5 ± 0.8^{ab}	0.7 ± 0.8^{a}	0.001
Standing 4th	1.2 ± 0.7^{b}	0.3 ± 0.5^{b}	< 0.001
Instep kicking	1.3 ± 0.7^{b}	0.7 ± 0.8	0.002
Standing 5th	1.2 ± 0.8^{b}	0.3 ± 0.5^{b}	< 0.001
Jumping	1.7 ± 0.7^{a}	1.0 ± 0.8^{a}	0.002
Standing 6th	1.2 ± 0.9^{b}	0.5 ± 0.6^{ab}	0.001

N = 21; a, b or c represents statistically identified groups classified by Duncan test among the postures/motions. Data are expressed as mean ± SE

The dispersion of skin pressure around the knees and calves while wearing the knee guards would be beneficial especially when landing after jumping.

Increased skin pressure by wearing knee guards: comfort vs. discomfort

In the present study, skin pressure increased by 3 times while wearing the knee guards compared to the control condition, but the absolute value (on average 18.3 mmHg; 7.5–27.4 mmHg) was mild enough not to restrict skin blood flow, knee joint movements, or induce pressure discomfort. For example, a skin garment pressure over 40 mmHg restricts skin blood flow of the calves or toes (Mayrovitz et al., 2003). According to Denton (1972), over 32.3 mmHg in garment pressure can induce pressure discomfort, but subjects felt pressure comfort between 14.7 and 29.4 mmHg. Under garments with the pressure of 30–40 mmHg can cause pressure discomfort (Makabe et al., 1991).

Increased or decreased skin blood flow from wearing knee guards

The second novel finding in the present study was that the increased rates of skin blood flow during dynamic soccer motions while wearing knee guards varied according to the body regions. On the thigh and calf, the increase rates were restricted by wearing the knee guards, while on the knee, the increase rates were accelerated by wearing the knee guards. Because skin compression could induce the restriction in skin blood flow, the responses from the thigh and calf could be anticipated. The inverse responses from the knee may be attributable to the anatomical composition of the knee and superficial blood redistribution due to the compressed blood vessels in the thigh and calf. Mayrovitz and Larsen (1997) found that the muscle blood flow of the tibialis anterior decreased from 10–35 mL·100 g^{-1} min^{-1} without compression to 5–11 mL·100 g^{-1} min^{-1} with compression during exercise. They insisted that the forefoot-to-knee compression bandaging caused an increase in the bandaged leg pulsatile blood flow, and suggested that a compression-associated pulsatile flow increase may play a role in the beneficial effects of compression bandaging in venous ulcer treatment. Wearing compression sleeves on forearms increased arterial perfusion by more than 200% compared with the control (contralateral forearm without compression), and its applied pressure of ~20 mmHg resulted in the largest flow increase (Bochmann et al., 2005). These data indicate that a pressure range may exist for blood flow augmentation, whereby pressures too low result in no change, and pressures too high have adverse effects. Wearing compression garments applied resultant compression of underlying tissues reduce transmural pressure in local arterioles, causing vessels to reflexively relax, thereby increasing blood flow (MacRae et al., 2011). Those were the results of vessel blood flow, not skin blood flow and unfortunately, and there were needed more evidence about the relationship between skin blood flow and skin pressure.

However, any physiological mechanism under the inverse response in the present study could not be elucidated using the current results. One definitive conclusion from the current results is that increased skin blood flow (%) from wearing the knee guards with an average pressure of 18 mmHg might be beneficial for knee joint movements during various soccer motions.

Skin pressure sensation

Garment pressure perception is an important factor when choosing compression fit garments for athletes or patients needing rehabilitation. In the present study, subjects felt greater skin pressure sensation while wearing the knee guards than the control condition, but the pressure sensations were not proportional to the results from skin pressure (mmHg) during the various positions and motions. That is, skin pressure had the greatest value for the sitting position among the 11 positions and motions, while subjects did not feel greater skin pressure sensation in the sitting position than in other positions or motions. Rather, subjects expressed greater pressure sensation during jumping or switching directions, which indicates that objective pressure value is not a single factor for the pressure sensation but there are other multiple factors (e.g., skin strain, covered surface area, or fabric characteristics) to affect the skin pressure sensation. You et al. (2002) found a logarithmic relation between pressure sensation and measured pressure in mmHg. Interestingly, however, they concluded that such relationships cannot be obtained when skin strain increases due to the movement of critical strain body areas (e.g., the knee or elbows). In addition to the skin strain factor the covered surface area (Makabe et al., 1991) and fabric characteristics (Ito et al., 1995) could be influential factors for the skin pressure sensation.

Conclusions and suggestions

The main findings of the present study are as follows: (1) increases in skin pressure from wearing the knee guards were less manifested during dynamic motions (e.g., kicking, switching directions, and jumping) when compared to static positions (e.g., sitting and standing), (2) increased rates in skin blood flow from wearing knee guards during soccer motions varied according to the body regions (increases for the knee but decreases for the calf and thigh), and (3) skin pressure sensation while wearing the knee guards was not consistent with the objective value of the skin pressure under the knee guards. Even though many unknown intertwined factors may underlie the present findings, a couple of explanatory factors could be as follows. Firstly, skin pressure due to the knee guards was maintained at a mild level (on average 18.3 mmHg). Secondly, skin blood flow when wearing knee guards showed smaller fluctuation among various body regions during the dynamic soccer motions. Further works were needed to elucidate the positive effects of wearing knee guards on performance and the underlying mechanism of the changes.

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Authors' contributions

YJB performed the experiment with human subjects, analyzed the data, and drafted the manuscript. HJ performed the human subject trials and data collection. JYL conceptualized the entire research and design, and the critical revision of the article. KWO conceptualized the entire research and design, and the critical revision of the article. All authors read and approved the final manuscript.

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Availability of data and materials
The datasets generated during and 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.

Ethics declarations
This research was conducted under the exemption and supervision of Seoul National University Institutional Review Board (IRB Exemption No.2008/001-007) regarding ethical issues including consent to participate.

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