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RESEARCH

A multidimensional approach to wearability assessment of an electronic wrist bracelet for the criminal justice system

Soo-Min Lee[1,2], So-Hyun Lee[1] and Juyeon Park[1,2,3*]

*Correspondence:
juyeon.park@snu.ac.kr

[1] Department of Textiles, Merchandising and Fashion Design, Seoul National University, 1 Gwanak-ro, Gwanak-gu, Seoul 08826, Republic of Korea
[2] Soft Robotics Research Center, Seoul National University, 1 Gwanak-ro, Gwanak-gu, Seoul 08826, Republic of Korea
[3] Research Institute of Human Ecology, Seoul National University, 1 Gwanak-ro, Gwanak-gu, Seoul 08826, Republic of Korea

Abstract

Electronic monitoring systems have been globally adopted to track criminals to ensure public safety efficiently. In this study, we aimed to assess the wearability of an electronic bracelet using multiple evaluation methods, including the evaluation of range of motion (ROM), air gap (AG), and clothing pressure (CP) at the wearer's wrist, as well as self-scoring of subjective comfort (SC). We recruited eight Korean male participants (N = 8) who were in their 30 s and did not have any musculoskeletal problems at data collection. We compared the test results collected on the first day with those obtained after wearing the electronic wrist bracelet for 5 consecutive days. We also examined the differences between the normal-weight and overweight groups. Overall, the data evinced a decrease in the wrist ROM, AG, and SC, but an increase in the CP after it was worn for 5 days. And, the results were more observable in the overweight group, as compared to the normal-weight group. Furthermore, this study proposed a novel and effective assessment tool that could be used to measure the wearability of devices or systems intended to be worn on the human body—not only the electronic wrist bracelet for criminal monitoring but also popular commercial electronic bracelets for sportswear or health-related monitoring system.

Keywords: Electronic wrist bracelet, Wearability, Range of motion, Air gap, Clothing pressure, Body mass index

Introduction

In the criminal justice system, electronic monitoring technology has been adopted for tracking criminals to ensure public safety (Crowe et al., 2002; Laster, 2014). The use of this monitoring system was initiated in Europe, the United States, and South America in the 1980s. Moreover, as a result of the increasing number of criminals worldwide, the electronic wearable device is currently being widely adopted in more than 30 countries (Bartels & Martinovic, 2017; Hucklesby et al., 2016; Nellis, 2021; Nellis et al., 2013; PEW, 2016). The electronic tagging device with a global positioning system (GPS) has been specially used for detention, restraint, and surveillance of criminals by attaching the device to their ankle or wrist (Di Tella & Schargrodsky, 2013; Hwang et al., 2021). Further, Akrap (2016) and Hickman et. al. (2010) determined that introducing an electronic monitoring system could increase the monitoring efficiency, which ensures the safety of both inmates and prison officers. In particular, the application of electronic monitoring systems to sex offenders reduced the recidivism rate of the same type of crimes (Belur et al., 2020; Gies et al., 2012). Additionally, Dew (2008) presented a successful case of reduced gang violence in prisons by adopting such a wearable monitoring system, which prevented the inmates from gathering in one location. Furthermore, Henneguelle et. al. (2016) reported that the electronic monitoring systems could be a cost-effective alternative to short-term imprisonment and can reduce long-term recidivism. That is, reducing overcrowding in prisons (Cara, 2020; Haverkamp & Woessner, 2016) may ultimately contribute to a decrease in imprisonment costs (Bhatia, 2021; Button et al., 2009).

Despite its critical function of real-time monitoring and surveillance, recent studies have reported that there is an increased number of instances of criminals escaping by removing the electronic monitoring device (Lawrence, 2020; Morabito, 2019; Ser & Kim, 2021). One of the primary reasons for such incidents could be due to its lack of wearability. To explain, electronic monitoring devices may cause physical shock or pain in wearers, especially when it is worn for a prolonged period. Additionally, they are known to cause skin irritation and rashes at the contact areas with the body. Moreover, it may also lead to convulsions and headaches (Albert, 2019; Rachel, 2019). To mitigate this problem, the researchers have explored various methods to improve the wearability of electronic monitoring devices. For example, Hwang et. al. (2021) conducted a subjective evaluation of an electronic monitoring device's wearing experience based on interviews with criminals, wherein the weight and large volume of the device were identified as the determinant factors causing uncomfortable wearing experiences. Martinovic and Schluter (2012) determined that the perception of wearing the device on the body caused physical strain while performing daily activities, including sleeping.

In addition to physical discomfort, it is also known to affect the psychological well-being of the wearers (Mair et al., 1990; Vanhaelemeesch et al., 2014). That is, psychological distress such as shame and anxiety could be caused by wearing the monitoring devices for prolonged periods, which could further affect the wearer's social life (Bhatia, 2021; Hwang et al., 2021; Nancarrow & Modini, 2018; Vanhaelemeesch et al., 2014). In extreme cases, prolonged wearing of such a device could lead to suicide tendencies. In fact, the suicide rate of monitored criminals was found to be 20 times higher than that of the general population in South Korea (approx. 0.029% of the total population), where the suicide rate is one of the highest among the countries of the Organization for Economic Co-operation and Development (OECD) (Park, 2016). Despite the seriousness of the side effects of electronic monitoring devices, only a limited number of studies have been conducted in examining the impact of prolonged wearing of electronic monitoring systems on the wearers (Martinovic & Schluter, 2012; Nellis, 2021). Moreover, to date, no assessment method that quantifies the wearability of an electronic monitoring device has been developed, except for the survey questionnaire that relies on one's subjective evaluation. Therefore, considering that the monitoring function and wearability are both equally important, we believe that it is necessary to develop a reliable assessment protocol for testing the wearability of the electronic monitoring systems to be used in the criminal justice system, as the first step to comprehend the issues associated with wearing such devices on humans.

Wearability assessment is a complex matter, as it involves multiple factors that affect the human-system interaction, such as the wearer's anthropometric dimensions, joint movements, pressure points, and subjective sensations (Dunne & Smyth, 2007; Gemperle et al., 1998). In other words, a wearable device should fit the wearer well; it should not limit the wearer's mobility nor constrain the blood circulation, causing excessive pain points (Mitsuno & Kai, 2019; Zhang et al., 2002, 2015). Furthermore, it should consider human body characteristics such as curvature, thickness, and body mass index (BMI), which vary by individuals (Hajime et al., 2007; Wang et al., 2019; Zhang et al., 2015). Additionally, subjective sensations should be considered a critical and final verdict of one's perceived wearability of a wearable device (Kekade et al., 2018; Wen et al., 2017) because how one feels comfortable or not is determined by the human in the end.

In simple words, to realize sufficiently high wearability in a wearable device, it must have a good balance across all the affecting factors. In this respect, we emphasize the importance of assessing the wearability of a wearable device from a multidimensional perspective, rather than a unidimensional one, as opposed to the approach that most previous studies have adopted. To this end, we aimed to (1) develop a multidimensional wearability assessment protocol and (2) perform the wearability assessment of a specific wearable monitoring case, i.e., an electronic wrist bracelet designed to be used in the criminal justice system. The electronic wrist bracelet, which is currently being tested in prisons, was provided by an industry partner and manufacturer searching of a human-centered design solution to improve the wearability of the product of interest.

Methods

Participants

We recruited eight Korean men (N = 8) who were in their 30 s and did not have any musculoskeletal problems at the time of data collection. The population was selected given that they represented the group with the highest crime rate in 2020, according to the Korean Statistical Information Service (KOSIS, 2020). We then divided them into the two BMI groups—normal-weight and overweight, to gauge the effect of body mass on wearability. All participants were right-handed. The study was approved by the Seoul National University's Institutional Review Board (IRB No. 2108/002-005), and the participants were informed of the experimental procedures and measurement postures prior to signing the written informed consent. The average age of all participants was 32.88 years old (± 2.15). The mean height was 174.86 cm (± 4.30) and the mean weight was 71.81 kg (± 11.04). The BMIs of the comparison groups were 21.03 kg/m^2 (± 1.03)

Table 1 Demographic characteristics of the study participants

Participants [mean (SD)]	Age (years)	Height (cm)	Weight (kg)	BMI (kg/m^2)
BMI 18.5–24.9 (n = 4)	33.00 (2.65)	173.50 (2.89)	63.23 (1.51)	21.03 (1.03)
BMI 25.0–29.9 (n = 4)	31.67 (2.08)	177.00 (6.08)	83.27 (4.26)	27.00 (1.10)
Total (N = 8)	32.88 (2.15)	174.86 (4.30)	71.81 (11.04)	24.01 (3.34)

BMI body mass index, *SD* standard deviation vs. 27.00 kg/m^2 (± 1.10). Table 1 summarizes the demographic and physical profile of the participants.

Experimental procedures

All participants visited the laboratory twice—on the first day and after wearing the electronic wrist bracelet for 5 consecutive days. The wearing period was decided based on the result of a previous study (Areia et al., 2020), where when healthy adult volunteers were required to wear different commercial wristband-type ambulatory vital sign monitoring devices for 72 h each, they ended up wearing them only for 70.6–90.0% of the planned wearing duration, when they were allowed to remove the device. On the other hand, criminals must keep on an electronic wrist bracelet in their daily lives with no option to remove it. Considering that the electronic wrist bracelet of our concern was actually intended to be worn by criminals, and yet the study participants were ordinary people who needed to wear it during their day to day activities, we thought the wearing period of 5 consecutive days totaling 120 h was reasonable in this study.

The multidimensional assessment protocol used in this study comprised the four wearability attributes, including the joint range of motion (ROM), air gap (AG), clothing pressure (CP), and subjective comfort (SC). Currently there is no standard protocol nor a tool to assess a wearable device's wearability. Hence, we developed a comprehensive measurement protocol to quantify critical functional dimensions of wearability for the devices that are intended to be worn on the human body. In the assessment protocol, we adopted a mixed-methods approach to generate a holistic perspective on the wearability of the electronic wrist bracelet. Namely, we included the joint ROM to measure the wrist movement; and the AG and CP to gauge the degree of friction, based on the force of pressure at the contact area between the bracelet and the wrist. Additionally, we incorporated a survey questionnaire to appraise the participants' subjective evaluation on the device's wearability.

On the first day, we measured all four attributes as a baseline reference to the data measured after 5 days of wearing the electronic bracelet. Specifically, when the participants visited the lab for the first time, we asked them to wear the bracelet and collected data for the assessment of the AG and CP. The two attributes were measured with the bracelet on to determine how the degree of swelling affects the location of the contact area and force of pressure by comparing the baseline data collected on the first day vs. those after the 5-day wearing period. On the other hand, we measured the ROM without wearing the bracelet to assess the change in the magnitude of the biomechanical behavior after 5 days in a natural (or unconfined) setting. To wit, if it was measured with the bracelet on, the wearer's wrist ROM could otherwise be restricted by the dimensions of the electronic device substantially.

In order to assess the wearing effect of the electronic wrist bracelet, the participants were asked to revisit the lab again upon the end of the wearing period and performed the same experiment as they did on the first day. To keep the bracelet's tightness across the participants consistent, the same researcher (i.e., the first author) put the device on each participant's wrist, only allowing a narrow distance between the device and wrist that is the same size as the thickness of a single air pack sensor (exactly 3 mm), which was later used for the CP measurement during the main experiment.

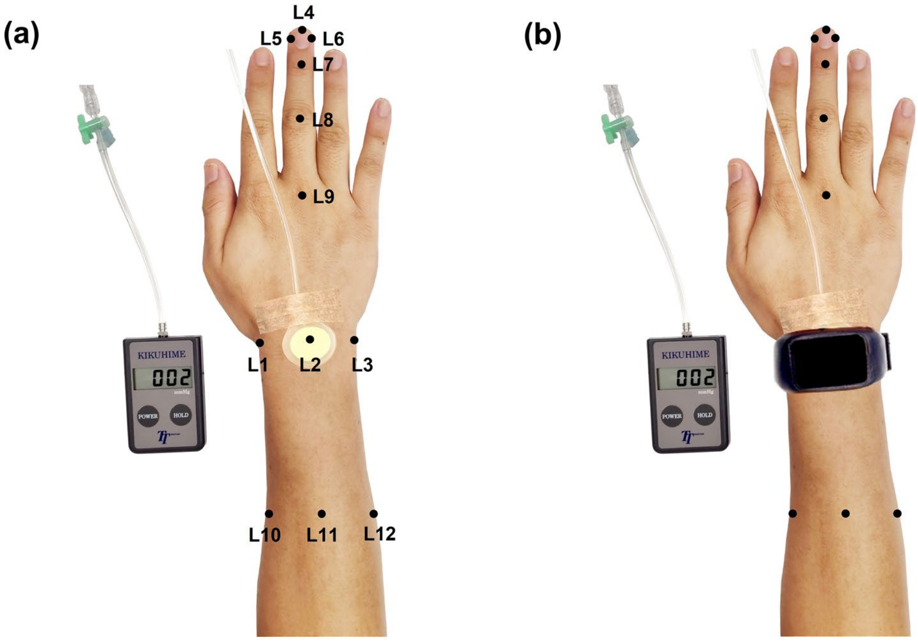

Fig. 1 Landmarks and the position of a clothing pressure sensor: (**a**) before wearing a bracelet (with landmark ID numbers) and (**b**) after wearing a bracelet

Once a participant put on the wrist bracelet, we marked 12 landmark points on the participant's right hand (Fig. 1) with henna ink to visually ensure the same locations for the measurements after 5 days of wearing. As illustrated in Fig. 1, the landmarks consisted of the three points at the wrist, including the radial styloid, ulnar styloid, and center of the radiocarpal joint (see Fig. 1a, L1–L3); the six points at the middle finger including the finger joints, the tip and each side of the nail (see Fig. 1a, L4–L9); and the three points at the midline between the wrist and the elbow (see Fig. 1a, L10–L12), parallel to the three wrist points. We selected the three wrist points L1–L3 as they were suggested by previous studies as the critical landmarks for wrist ROM measurements (Griffin et al., 2018; Labat & Ryan, 2019; Reissner et al., 2019); and we additionally included the other landmarks at the middle finger and forearm to assist data retrieval from the 3D-scanned hand models for ROM analysis.

For the wrist ROM measurement, we asked the participants to perform four particular wrist postures—flexion, extension, radial deviation, and ulnar deviation, which were adopted from previous studies (Klum et al., 2012; Labat & Ryan, 2019; Nelson et al., 1994; Ryu et al., 1991) (Fig. 2). A 3D body scanner (Artec Eva; Artec3D, Luxembourg) was used to measure the wrist ROM. Flexion posture is a downward bending motion of the wrist, whereas the extension posture pulls the dorsal surface of the hand to the highest possible extent. Radial and ulnar deviations are the postures of moving the wrist maximally in the radial and ulnar styloid directions toward the thumb and little finger, respectively. To pose the postures, the participants sat on a chair with their right arm comfortably resting on a measuring desk without arm abduction or adduction. Then the arm was fixed to the measurement plate during measurements. The participants were asked to use only the wrist joint to set the postures. During the experiment, a splint

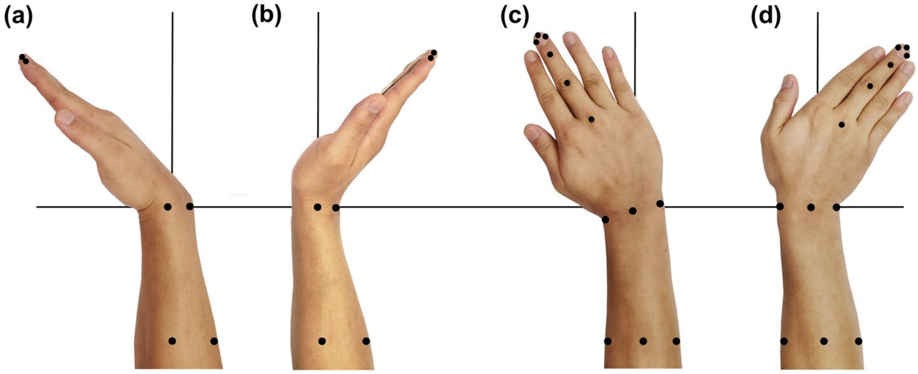

Fig. 2 Measurement postures for the wrist range of motion: (**a**) flexion, (**b**) extension, (**c**) radial and (**d**) ulnar deviations

Table 2 Experimental procedure

Participants (N = 8)	Stage 1	Stage 2	Stage 3	Stage 4
Status	Before and after wearing the bracelet	While wearing the bracelet	Before and after wearing the bracelet	Subjective evaluation through questionnaire
Posture	Four ROM postures		Six daily activities	
Measurement items	ROM	AG	CP	SC

ROM range of motion, *AG* air gap, *CP* clothing pressure, *SC* subjective comfort

was placed on the palm to prevent it from bending, thereby minimizing the error in the measurement postures. Table 2 illustrates the experimental procedures adopted in this study.

Subsequently, we used the reverse-engineering software (Geomagic Design X; 3D Systems, Rock Hill, SC) in the same ROM postures to measure the AG while wearing the bracelet; the cross-sectional area of the bracelet-wearing part was extracted. As we described earlier, regarding donning of the wrist bracelet, we attached the air pack sensor to the wrist on the back of the hand, where the center of the electronic bracelet monitor was pressed to measure the CP (Kikuhime TT Meditrade; Soleddet 15, DK 4180 Soro). Given the relatively large size of the air pack sensor (20 mm in diameter), in relation to the wrist, we decided to attach it to the dorsal (top) side of the participant's wrist to ensure that the sensor was laid flat for stable data retrieval. The CP was measured before and after wearing the bracelet in the four ROM postures while performing the six daily activities for 1 min each. Figure 3 illustrates the six daily activities, which were selected based on the performance frequency in daily lives, as guided by Kanna et. al. (2016). They included standing, stretching, jogging, writing, eating, and box-lifting. The standing activity refers to standing still with the arms lowered comfortably, whereas the stretching activity involves reaching out and raising the hands above the head. Jogging activity indicates a light jogging motion to the extent that "the degree of motion is very light" in the subjective motion recognition of Borg (1988). The writing activity involved writing specific content on paper using a pen, and the eating activity was performed using a spoon. The box-lifting activity involved lifting a box weighing 5 kg from a chair and placing it back on the chair.

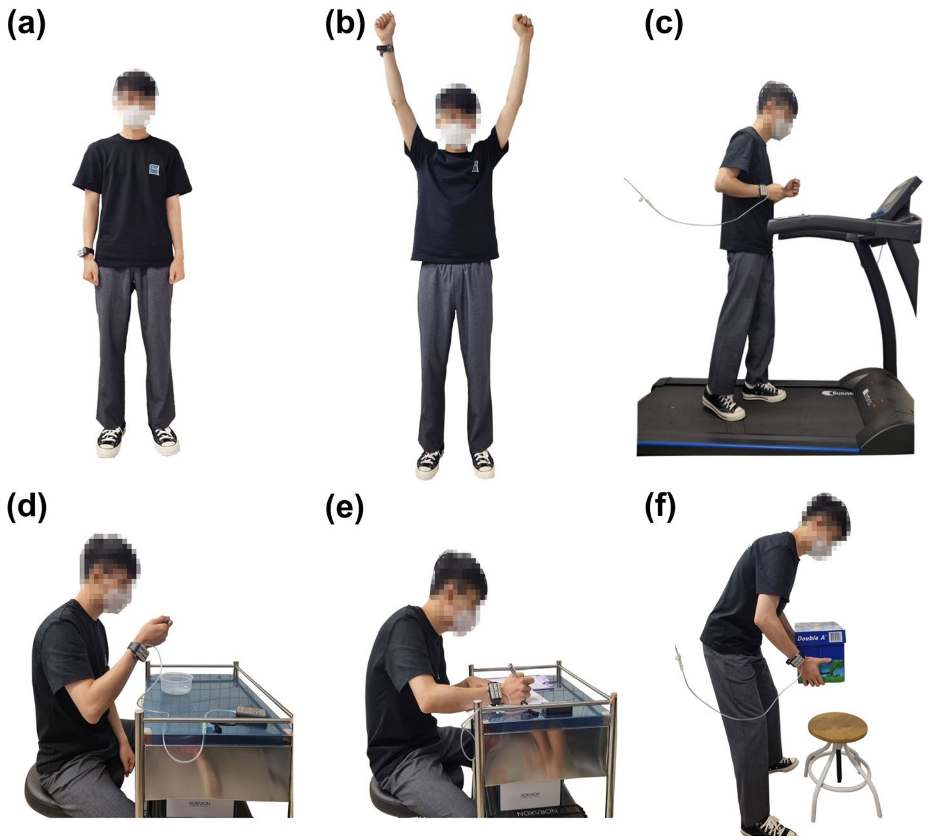

Fig. 3 Daily activities performed: (**a**) standing, (**b**) stretching, (**c**) jogging, (**d**) eating, (**e**) writing and (**f**) box-lifting

Additionally, the participants were asked to fill out an online questionnaire, which was used to evaluate the SC perception experienced during the required experiment on the first day and after 5 days of wearing the bracelet. The questionnaire items were prepared based on the Comfort Rating Scales (CRS) proposed by Alessi et. al. (2017) and Knight and Baber (2005), which consisted of a total of 18 items, with four items regarding appearance, two items on pressure/scratch, and 12 items on comfort (with 6 sub items), all measured on a 5-point Likert scale (Table 3).

Data analysis

We used the SPSS 26.0 (IBM SPSS Statistics 26, USA) and Excel 2019 (Microsoft Excel, USA) to analyze the data. We generated descriptive statistics to see the overall trends in data, and performed the Shapiro–Wilk tests to verify the normal distribution of the data sets. When normality was observed, we compared the mean differences of the measurement results based on paired-samples t tests (before vs. after) and independent-samples t tests (normal-weight vs. overweight). When normality

Table 3 Questionnaire items for SC evaluation

Item	Question
Appearance	The size of the electronic bracelet lock is appropriate[a]
	The thickness of the electronic bracelet strap is appropriate[a]
	Overall, I like the design of the electronic bracelet[a]
Pressure/scratch	I feel scratching on my wrist due to the size problem of the electronic bracelet
Comfort	
Emotion	I feel tense or on edge because I am wearing the electronic bracelet
Attachment	I feel the electronic bracelet moving
Harm	The electronic bracelet is painful to wear
Perceived change	I feel strange wearing the electronic bracelet
Movement	The electronic bracelet inhibits or restricts my movement
Anxiety	I feel being monitored when I am wearing the electronic bracelet

[a] Reversed items

Table 4 Changes in the wrist ROM before and after wearing on the first day

ROM [°, mean (SD)]	Non-wear	Wear	Difference	Δ (%)	z	*p*
Total (N = 8)	33.37 (14.83)	31.23 (14.64)	− 2.14 (2.45)	**6.41**	**− 3.79**	**0.000**

Items in bold: significant t-value

ROM: range of motion; SD: standard deviation; Δ: delta

was not observed, we adopted Wilcoxon signed-rank (before vs. after) and Mann–Whitney U tests (normal-weight vs. overweight). Additionally, we conducted one-way ANOVA tests for the mean comparisons on two or more variables (e.g., the AG by wrist regions). All statistical analyses were performed at the 95% confidence level.

Results

Range of motion (ROM) at the wrist

Since the *p* value of the Shapiro–Wilk test was less than 0.05, the normality of the ROM data on the first day was not observed. Therefore, we performed the Wilcoxon signed-rank test to compare the wrist ROM when the wrist bracelet was worn or not worn on the first day. The statistical results showed that the wrist ROM of the participants was reduced as much as 6.41% when the bracelet was worn versus when it was not worn ($z = -3.79$, $p = 0.000$), signifying that the movement of the wrist joint was negatively affected even by simply wearing the electronic wrist bracelet (Table 4) as the current proof shows.

Further, we compared the changes in the wrist ROM before and after wearing the bracelet for 5 days, respectively (Table 5). Because normality was not observed, we performed the Wilcoxon signed-rank test. Overall, we observed a decrease in the wrist ROM of as much as 7.13% ($z = -3.81$, $p = 0.000$) after 5 days of wearing it and compared them to that measured on the first day, which indicates that the movement at the wrist was negatively affected by wearing the bracelet for 5 days. The same trend was also found in both BMI groups. That is, it decreased by 6.23% in the normal-weight and 8.10% in the overweight groups, which were significant at $p < 0.05$.

Table 5 Changes in the wrist ROM after 5 days of wearing

ROM [°, mean (SD)]	First day	After 5 days	Difference	Δ (%)	z	*p*
Total (N = 8)	33.37 (14.83)	30.99 (13.61)	− 2.37 (3.14)	**7.13**	**− 3.81**	**0.000**
Normal-weight (n = 4)	34.38 (15.83)	32.24 (14.87)	− 2.13 (3.42)	**6.23**	**− 2.64**	**0.008**
Overweight (n = 4)	32.36 (14.21)	29.74 (12.59)	− 2.61 (2.93)	**8.10**	**− 2.74**	**0.006**

Items in bold: significant t-value

ROM: range of motion; SD: standard deviation; Δ: delta

Additionally, Table 6 presents the changes in the ROM before and after wearing the bracelet for 5 days based on the four measurement postures. Overall, the results of Wilcoxon signed-rank test showed decreased ROMs in all four postures after wearing the bracelet for 5 days, and the decrease rates were 0.19–4.39°, which was 1.40–10.30% reduction, as compared to the first day. Out of the four postures, the ROM decreased significantly in flexion and extension, but did not in radial deviation and ulnar deviation at $p < 0.05$. It could be interpreted that the participant's wrist movement was more affected when it bent upwards and downwards relative to inwards and outwards movement after wearing the electronic wrist bracelet for 5 consecutive days.

Fit analysis based on the air gap (AG)

We compared the AG results on the first day with the data collected after 5 days of wearing the bracelet using the paired-sample t test, and the difference between groups was compared using the independent-sample t test because the AG data were normally distributed. Table 7 presents the changes in the AG before and after wearing the bracelet for 5 days. The results of the AG show that overall it decreased marginally but it was not statistically meaningful ($p = 0.668$). However, when we looked at the results more closely, we found an interesting trend in the weight group data. That is, whereas the AG in the normal-weight group increased by 6.26% after the devices was worn for 5 days ($t = -2.25$, $p = 0.036$), the score in the overweight group decreased by 8.73% ($t = 2.77$, $p = 0.012$). Both statistics were significant at the 95% confidence level. This

Table 6 Wrist ROM measurements in different postures

ROM [°, mean (SD)]	First day	After 5 days	Difference	Δ (%)	z	*p*
Flexion	42.51 (7.50)	38.13 (7.47)	− 4.39 (2.05)	**10.30**	**− 2.52**	**0.012**
Extension	45.31 (12.67)	41.63 (13.95)	− 3.69 (3.39)	**8.12**	**− 2.52**	**0.012**
Radial	13.60 (6.05)	13.41 (4.85)	− 0.19 (3.06)	1.40	− 0.56	0.575
Ulnar	32.04 (3.71)	30.81 (2.46)	− 1.23 (2.28)	3.84	− 1.40	0.161

Items in bold: significant t-value

ROM: range of motion; SD: standard deviation; Δ: delta

Table 7 Changes in the AG before and after 5 days of wearing

AG [mm^2, mean (SD)]	First day	After 5 days	Difference	Δ (%)	t	*p*
Total (N = 8)	28.27 (4.40)	27.98 (5.29)	− 0.29 (4.27)	1.02	0.43	0.668
Normal-weight (n = 4)	29.08 (3.30)	30.90 (4.48)	1.82 (3.61)	**6.26**	**− 2.25**	**0.036**
Overweight (n = 4)	27.46 (5.24)	25.06 (4.39)	− 2.41 (3.88)	**8.73**	**2.77**	**0.012**

Items in bold: significant t-value

AG: air gap; SD: standard deviation; Δ: delta

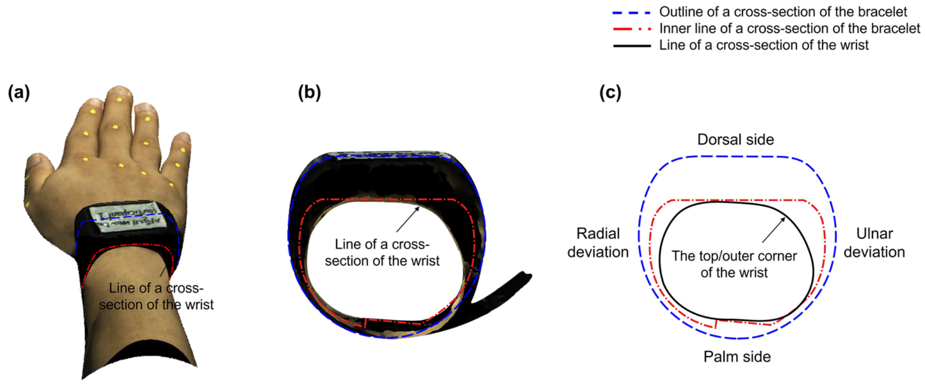

Fig. 4 Cross-sectional view of the wrist and bracelet: (**a**) 3D shape of an electronic bracelet worn on the wrist, (**b**) 3D shape of an electronic bracelet and (**c**) air gap locations in a cross-section

Table 8 Differences in the AG by wrist regions

AG [mm^2, mean (SD)]	Landmarks				F	*p*
	Dorsum–Ulnar	Dorsum–Radial	Palm–Ulnar	Palm–Radial		
Total (N = 8)	9.54 (2.34)^a	7.52 (1.84)^b	6.09 (2.43)^c	4.97 (2.34)^d	**62.89**	**0.000**
Normal-weight (n = 4)	9.29 (1.71)^a	8.31 (1.53)^b	6.64 (2.59)^c	5.76 (1.97)^d	**52.51**	**0.000**
Overweight (n = 4)	9.79 (2.84)^a	6.74 (1.81)^b	5.54 (2.14)^c	4.19 (2.23)^d	**43.72**	**0.000**
Comparison between groups						
t	0.957	4.193	2.058	3.329		
p	0.342	**0.000**	**0.043**	**0.001**		

Items in bold: significant t-value; the alphabetical order is the same as the order of mean difference according to the Duncan test

AG air gap, *SD* standard deviation

contrasting outcome in the AG by the BMI groups could be explained by the unique variance of human adaptation with the prolonged wearing of wearable devices—e.g., edema vs. loss of muscles (Akima et al., 2001; Motobe et al., 2004), which is further elucidated in "Discussion".

In order to discern the specific contact points of the bracelet at the wrist, we measured the AG at the four wrist locations—i.e., the dorsum-ulnar, dorsum-radial, palm-ulnar, palm-radial (see Fig. 4). We then conducted a one-way ANOVA test to compare the AG scores at the landmark points. The results indicated significant differences in the AG scores at the four landmarks (F = 62.89, $p = 0.000$). Specifically, the AG at the dorsum-ulnar point of the wrist was the largest, followed by the dorsum-radial, palm-ulnar, and palm-radial point. The results were true in both BMI groups (F = 52.51, $p = 0.000$; F = 43.72, $p = 0.000$) (Table 8). In addition, when comparing by the BMI groups, the AG was significantly greater at the dorsum-radial, palm-ulnar, and palm-radial points among the normal-weight participants ($p = 0.000$, 0.043, 0.001 respectively), but there was no significant difference at the dorsum-ulnar point between the groups ($p = 0.342$). To elaborate, while the highest gap space was found at the top/

Table 9 CP measurements before and after 5 days of wearing

CP [mmHg, mean (SD)]	First day	After 5 days	Difference	Δ (%)	z	*p*
Total (N = 8)	28.09 (13.77)	30.91 (17.10)	**2.82 (16.05)**	**10.04**	**– 6.76**	**0.000**
Normal-weight (n = 4)	27.84 (13.34)	28.49 (12.44)	0.66 (13.21)	**2.33**	**– 2.94**	**0.003**
Overweight (n = 4)	28.34 (14.19)	33.32 (20.47)	4.98 (18.20)	**17.57**	**– 7.16**	**0.000**

Items in bold: significant t-value

CP: clothing pressure; SD: standard deviation; Δ: delta

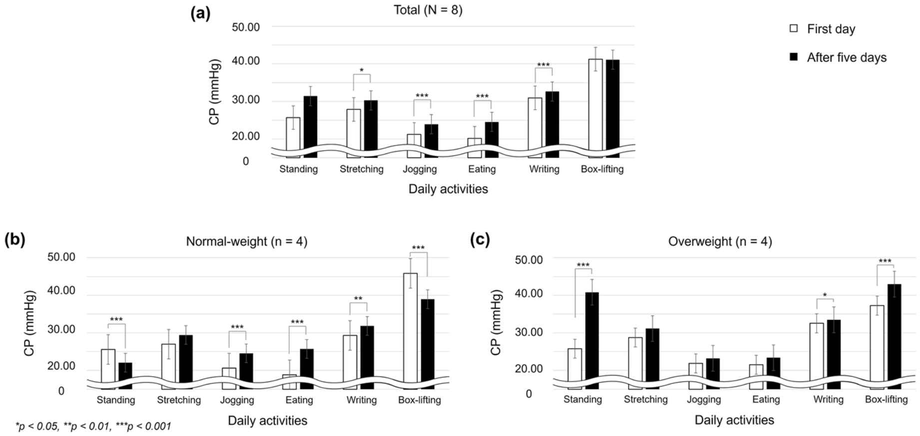

Fig. 5 Results of clothing pressure by different daily activities

outer corner of the wrist in both BMI groups, significantly higher gap space was noticeable at the other three landmark points among the normal-weight participants than the overweight participants. The cross-sectional view in Fig. 4 illustrates the overall trends of the AG scores at the four wrist landmarks.

Clothing pressure (CP) during daily activities

We compared the CP results collected while performing the six daily activities with the bracelet on, on the first day vs. after 5 days of wearing the electronic device using the Wilcoxon signed-rank test (Table 9). Overall, the CP increased after the 5-day wearing period by as much as 2.82 mmHg (3.76 hPa, 10.04%), which indicated the increased force of pressure inside the bracelet ($z = -6.76$, $p = 0.000$). This result was more noticeable in the overweight group than in the normal-weight group at the 95% confidence interval ($z = -2.72$, $p = 0.007$).

To determine the effect of wearing the electronic wrist bracelet for 5 days, we analyzed the change rates of the CP during the six daily activities using the Wilcoxon signed-rank test (Fig. 5). Overall, the highest CP was found in box-lifting (41.24 mmHg, 54.98 hPa) both on the first day and after 5 days of wearing, while the lowest scores were observed in jogging (21.21 mmHg, 28.28 hPa) and eating (20.18 mmHg, 26.90 hPa). While the CP scores remain similar in the box lifting activity before and after wearing the bracelet, they tended to increase in all other activities. Of the six activities, the most affected was stretching ($z = -2.01$, $p = 0.045$), followed by jogging ($z = -5.43$, $p = 0.000$), eating ($z = -6.51$, $p = 0.000$), and writing ($z = -3.92$, $p = 0.000$). As visualized in Fig. 5,

Table 10 Changes in the SC before and after 5 days of wearing

SC [score SD)]	First day	After 5 days	Difference	Δ (%)	z	*p*
Total (N = 8)	1.75 (1.38)	2.13 (1.51)	0.38 (1.69)	**21.71**	**− 2.73**	**0.006**
Normal-weight (n = 4)	1.81 (1.40)	1.62 (1.41)	− 0.19 (1.35)	10.50	− 1.37	0.170
Overweight (n = 4)	1.68 (1.36)	2.64 (1.44)	0.95 (1.69)	**57.14**	**− 4.62**	**0.000**

Items in bold: significant t-value

ROM: range of motion; SD: standard deviation; Δ: delta

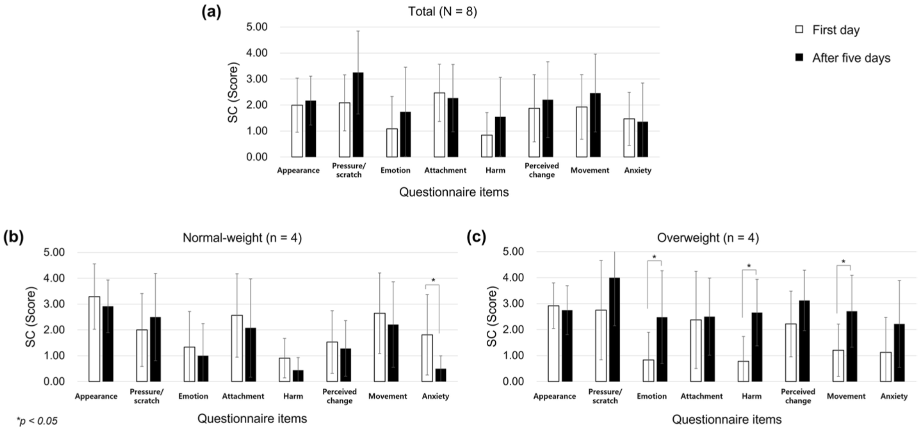

Fig. 6 Results of subjective evaluation by questionnaire items

within the normal-weight group, after wearing the bracelet for 5 days, the CP increased in the three daily activities, including jogging (z = − 6.31, $p = 0.000$), eating (z = − 8.55, $p = 0.000$), and writing (z = − 3.32, $p = 0.001$) activities, but decreased in standing (z = − 5.11, $p = 0.000$) and box-lifting (z = − 3.94, $p = 0.000$) activities after 5 days. On the other hand, in the overweight group, the CP tended to increase in all six activities—for example, in standing (z = − 6.57, $p = 0.000$), writing (z = − 2.04, $p = 0.041$), and box-lifting (z = − 3.58, $p = 0.000$) activities.

Subjective comfort (SC)

Table 10 shows the SC ratings obtained on the first day and after wearing the electronic wrist bracelet for 5 days through the Wilcoxon signed-rank test. Overall, the total scores showed negative changes in the participants' SC ratings (z = − 2.73, $p = 0.006$). By the BMI groups, while the overweight participants indicated significantly negative responses on SC after 5 days of wearing (z = − 4.62, $p = 0.000$), the normal-weight participants' responses did not show such significance at the 95% confidence level (z = − 1.37, $p = 0.170$).

To examine the SC results more closely, we compared the means of the survey scores before and after the wearing period in the eight evaluation items. As depicted in Fig. 6, for the combined data, no significant difference was found in any of the eight items at $p < 0.05$. Namely, although the overall SC scores showed a negative trend in the participants' perception changes in the wearing comfort of the electronic wrist bracelet after wearing for 5 days (as seen in Table 10), it was not obviously observed in each of the evaluation items for the total group. However, within each BMI group, we found statistical significance in the following items: anxiety in the normal-weight group and emotion, harm, and movement in the overweight group. To explain, after wearing the electronic wrist bracelet for 5 days, the normal-weight participants tended to experience less anxiety with the device, meaning that they became adaptive with wearing it after 5 days. On the other hand, the overweight participants tended to feel more worried about wearing the electronic wrist bracelet (emotion), perceive it more harmful and painful (harm), and their body movement was restricted by the device (movement), compared to the first day.

Furthermore, we compared the SC scores between the BMI groups (Table 11). There were three items, out of eight, that showed strong significance in the comparisons of the SC scores by the BMI groups, which included pressure/scratch, harm, and perceived change. That is, the overweight participants rated more negatively on the aforementioned three items than the normal-weight participants at $p < 0.05$, signifying that people with higher BMI felt significantly more discomfort against their skin, more harmful, and more physically different than those with normal BMI.

Discussion

In this study, we evaluated the wearability of an electronic wrist bracelet that is currently being tested in prisons. To obtain a comprehensive understanding of the wearability of the wrist bracelet, we developed a multidimensional assessment protocol involving the four key attributes: joint movement (ROM), anthropometric fit (AG), skin pressure (CP), and subjective comfort (SC). We compared the test results collected on the first day with those obtained after wearing the electronic wrist bracelet for 5 consecutive days. We also examined the differences between the normal-weight and overweight groups. Overall, the data evinced a decrease in the wrist ROM, AG, and SC, but an increase in the CP after it was worn for 5 days. And, the results were more observable in the overweight group, as compared to the normal-weight group.

In particular, for the wrist ROM, higher decrease rates were observed in the flexion and extension postures than in the radian and ulnar deviations, which indicated that the wrist movement in the upwards/downwards directions was more affected by wearing the bracelet for a prolonged time than the movement in sideways, which was more

Table 11 Differences between groups in SC

SC [score (SD)] (N = 8)	Total (N = 8)	Normal-weight (n = 4)	Overweight (n = 4)	Difference	Δ (%)	z	*p*
Appearance	2.03 (1.04)	1.90 (1.15)	2.17 (0.91)	0.27 (0.21)	14.29	−1.07	0.286
Pressure/scratch	**2.81 (1.80)**	**2.25 (1.53)**	**3.38 (1.93)**	1.13 (0.62)	50.00	**−2.03**	**0.042**
Emotion	1.41 (1.50)	1.17 (1.30)	1.66 (1.67)	0.49 (0.43)	41.96	−0.93	0.354
Attachment	**2.37 (1.65)**	2.30 (1.73)	2.43 (1.63)	0.14 (0.59)	6.12	−0.36	0.719
Harm	1.20 (1.24)	**0.67 (0.70)**	**1.72 (1.46)**	1.05 (0.40)	155.81	**−2.00**	**0.046**
Perceived change	2.04 (1.34)	**1.41 (1.12)**	**2.67 (1.26)**	1.27 (0.42)	90.00	**−2.55**	**0.011**
Movement	**2.19 (1.50)**	2.43 (1.59)	1.96 (1.41)	−0.47 (0.43)	19.31	−0.83	0.405
Anxiety	1.41 (1.47)	1.16 (1.31)	1.67 (1.61)	0.52 (0.52)	44.59	−0.72	0.470

Items in bold: significant t-value

SC subjective comfort, *SD* standard deviation pronounced among the overweight participants than the normal-weight participants. The higher observation frequency in the overweight group can be explained by the effect of body fat and muscles on the wrist joint area, as overweight participants tended to have less wrist flexibility due to the excess amount of muscles and fat mass (Gilleard & Smith, 2007; Jeong et al., 2018). It is also known that in a prison environment, behavioral restrictions and nutritional imbalances could contribute to the prisoners' weight gain during detention (Battaglia et al., 2013; Clarke & Waring, 2012; Johnson et al., 2018) and exacerbate the increase of obesity in prisoners (Herbert et al., 2012; Plugge et al., 2009). Therefore, it is critical to pay particular attention to the ROM issues and associated difficulties in wearing an electronic wrist bracelet for a prolonged period in those with higher body mass. Moreover, the electronic wrist bracelet has typically been manufactured in one size with no size adjustability feature, which seems to have caused more negative wearing experiences among the prisoners with higher BMIs.

As the AG data demonstrated, after wearing the electronic bracelet for 5 days, the spatial margin between the wrist and bracelet decreased, and the trend was more noticeable in the overweight individuals, which could be explained by the fact that they are more prone to venous-lymphatic circulation abnormalities than normal-weight individuals, which leads to edema (Agus et al., 2005; Cemal et al., 2013) and other symptoms of wrist inflammation (Krabben et al., 2015; Luukkainen et al., 2007). On the other hand, the significant increase of the AG among normal-weight individuals—i.e., the thinness at the wrist area—might be considered as a phenomenon of human adaptation, which is similar to the side effect after wearing a cast or assistive device for a prolonged period, due to the loss of muscles (Akima et al., 2001; Motobe et al., 2004).

We also observed the effect of the different measurement postures and wrist regions on the AG after wearing the device for 5 days. Compared to the data on the first day, the AG decreased in the flexion and extension postures, in which the ROMs were also restricted. It is because performing the two postures tended to compress the particular wrist spots where the extrinsic muscle tendons, called retinacula and other tendon sheaths in the palmar region, were located (LaBat & Ryan, 2019). In addition, regardless of the participants' BMIs, the AG in the dorsum-ulnar region was the largest; thus, the bracelet appeared to put more pressure at the wrist spot that was tilted toward the center of the body. We infer that it might be due to the fact that the human body tried to adapt to the fixed shape and dimensions of the electronic wrist bracelet, which was made of hard materials, as depicted in Fig. 4. Furthermore, the gradual adaptation of the human body to the electronic device seemed to engender the pressure points on the wrist, as the participants wore it longer.

Along with the fixed shape and dimensions of the electronic wrist bracelet, the hard monitor of the bracelet which was bulky and positioned on the dorsal facade of the wrist, tended to put pressure on the skin contact area at the opposite of the radial and ulnar joints, thus causing swelling on the top side of the wrist. Further, the CP in the postures of daily activities showed an increasing trend after wearing the device for 5 days. Herein, the increase rate of the CP was greater in overweight individuals than normal-weight individuals. The results of this study affirmed that the spatial margin between the body and the electronic wrist bracelet was negatively associated with the skin pressure experienced, which was consistent with Zhang et. al. (2002)'s study. Additionally, the CP measured during all daily activities exceeded the threshold of the maximum preferred CP, of roughly 20 mmHg (26.66 hPa) (Mitsuno & Kai, 2019), after 5 days, and it increased as the movement level increased (e.g., box-lifting). The results confirmed that wearing an electronic wrist bracelet for a prolonged period caused discomfort for the wearers when they went on with their daily lives, as indicated by the passing threshold of the CP scores.

According to the findings on SC, overall, the participants reported negative experiences of wearing the electronic wrist bracelet after 5 days. For the comparison between the BMI groups, after the 5-day wearing period, the overweight participants reported that they were worried; they felt that the wearable was harmful and hindered their mobility; however, this was not reported in the normal-weight group. Interestingly the normal-weight participants seemed to become less anxious about the electronic wrist bracelet after wearing it for 5 days. In short, the results from the subjective evaluation on the electronic bracelet supported the outcomes of the experiments on the wrist ROM, AG, and CP, particularly in the overweight group.

Applying these findings to human-centered design, we first noticed that electronic bracelets are typically made of hard or sturdy materials to eliminate the possibility of breaking the bracelet and escaping (Dunne & Smyth, 2007; Hwang et al., 2021; Martinovic & Schluter, 2012). Thus, by design, the bracelets cannot be flexibly deformed to fit the shape of the wrist. However, as understood from this study, despite the inflexible shape of the wearable devices, the human body is flexible, and it can adapt to the wearing environment to a certain degree (Lundborg & Dahlin, 1996). Accordingly, the design of a symmetrical form of the wrist bracelets seemed to reduce the functional ROM at the wrist. Therefore, the shape of the bracelet must be adjusted to fit the cross-section of the wrist because a symmetrical shape inevitably reduces wearing comfort. Furthermore, the fixed monitor containing the main sensor board that is positioned on the dorsal side of the wrist can be designed to have a round shape or a shape that is more compatible with the curvature of the body, rather than the constrained symmetrical rectangular monitor, as the bracelet's monitor could further influence the wearer's usage (Bradley, 2013; Frey, 1949; Pinna, 2011; Wang & Hsu, 2019; Wang et al., 2021).

Conclusions

However, this study has several limitations to consider. That is, the wearability assessment was performed with healthy individuals in controlled experimental settings and not with its actual intended users in real conditions. Although this was due to current governmental restrictions regarding access to actual criminals or facilities, it would be desirable to validate the results of this study with the data collected from the actual population in real settings in the future. In addition, for the experimental design, we set the wearing duration for 5 consecutive days (totaling 120 h) with consideration for the study participants' physical and psychological well-being during the test period in a social context. However, we believe that the use of electronic monitoring systems for a longer duration could bring out additional issues related to wearability. In addition, age could be considered in the data collection, given the higher age of prisoners (Quarterly Crime Report, 2021).

Nonetheless, this study could offer positive contributions to research communities and society as a whole. Namely, the outcomes of this study propose a novel and effective assessment tool that could be used to measure the wearability of devices or systems intended to be worn on the human body—not only the electronic wrist bracelet for criminal monitoring but also popular commercial electronic bracelets for sportswear or health-related monitoring system, which otherwise is challenging to draw a holistic perspective on the complicated matter involving the human body, human mind, device characteristics, and interactions across all components. In conclusion, we believe it is necessary to improve the wearability of the electronic monitoring devices based on a keen understanding of the issues of current products from the human-centered design perspective. In particular, the relationship between the human body and wearable device must be carefully analyzed while proposing design suggestions for such wearable monitoring devices because they constantly interact with the body as a mediator between the body and environment (Bryson, 2009; LaBat & Ryan, 2019; Laing & Sleivert, 2002). We hope the practical knowledge we gained from the wearability assessment of the electronic wrist bracelet could be useful for developers and manufacturers to gauge opportunities to improve the design of wearable devices while offering the necessary body-device compatibility for its wearers.

Abbreviations

AG	Air gap
BMI	Body mass index
CP	Clothing pressure
GPS	Global positioning system
ROM	Range of motion
SC	Subjective comfort

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Author contributions

SML and JP contributed to the design and planning of the research. SML was responsible for collecting and analyzing the data and wrote the first draft of the manuscript. SHL assisted in data collection, participated in literature search, and provided feedback to the manuscript draft. JP supervised the overall research process, and revised the manuscript. All authors read and approved the final manuscript.

Authors' information

SML is a Ph.D. candidate in the Department of Textiles, Merchandising and Fashion Design at Seoul National University (SNU). Her research interests include development of ergonomic products, wearability assessment, and fabrication of various knitting patterns with shape memory alloy.
SHL is currently a master's student in the same department and university as the first author. All graduate students are associated with the Wearable Ergonomics and Anthropometrics Research Lab (WEAR lab) at SNU.
JP, Ph.D. is an Associate Professor in the Department of Textiles, Merchandising and Fashion Design and a Vice Director of the Soft Robotics Research Center at SNU. She is the principal investigator of the WEAR lab. Her research scholarship focuses on human-centered design, ergonomic development of wearable products, and human body anthropometry.

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Availability of data and materials

Raw data (image files and samples) generated for this study are available upon request from the corresponding author.

Declarations

Ethics approval and consent to participate

This research was conducted under the approval and supervision of the Seoul National University (IRB Approval No. 2108/002-005).

Competing interests

The authors declare that they have no competing interests.

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