Fashion and Textiles

RESEARCH Open Access

Innovativeness in tradition: a comparative study of traditional leather armor scales and modern materials

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Abstract

In medieval Korea, armors made of various materials were developed. Among these, the leather armors were lighter and cheaper than the iron armors and were easy to make. For these reasons, there was a movement toward replacing two-thirds of suits of iron armor with leather armor made of pig or cow skin. As a follow-up to a previous study in which the basic physical properties of a leather scale specimen were investigated, in this study, we focused on the protective performance of this material through a comparison with materials such as steel and polycarbonate. In particular, the superiority of the leather was verified through a quantitative comparison with a modern carbon fiber composite. As part of this study, armor that copied the shape of traditional *myeonpigap* was produced. Carbon fiber composite panels were used to coat this armor in order to satisfy the requirements for the armor to be light, wearable, and provide effective anti-stab protection at the same time.

Keywords: Leather armor, Scale, Carbon fiber, Composite, Anti-stab

Introduction

During the Joseon Dynasty in Korea (1392–1897), armor made of various materials was worn. Iron armor offered the best protection and was generally preferred, but not all soldiers could wear this type since it was expensive and difficult to manufacture. A large amount of armor was provided to the military camp called *Hullyeondogam* and this amounted to 839 suits of iron armor for cavalry and 2,892 suits of leather armor for infantry (Seo & Sim, 1808). It shows that leather armor, so-called *pigap* [皮甲] was the most widely used type during the late Joseon Dynasty. Although leather armor provided less effective protection than iron armor, it was warmer, lighter, and cheaper and was easy to make. Because of its weight, iron armor was uncomfortable to wear and difficult to transport in bulk. For those reasons, in the early Joseon Dynasty, there was a movement toward replacing two-thirds of suits of iron armor with leather armor made of pig or cow skin (Office of Royal Annals, 實錄廳, 1457).

The structure of leather armors changed during the Joseon Dynasty. In the early Joseon Dynasty, small leather scales were connected horizontally and vertically to form lamella armors; however, later, the leather scales were riveted inside the coat. The structure of the leather armors of the late Joseon Dynasty is described in the *Yungwonpilbi* [戎垣必備], a nineteenth century book on the military strategy of the Joseon Dynasty (Park, 1813). The interfacing was placed such that it held up the armor between the face and the lining of the short-sleeved cotton combat garment; the leather armor was attached inside to form a protective layer. Examples of these *pigap* [皮甲] with cotton combat garments, so-called *myeonpigap* [綿皮甲], are housed in the National Museum of Korea, the National Palace Museum of Korea, and Yonsei University Museum.

In this study, we aimed to produce a modern version of the traditional *myeonpigap* [綿皮甲] based on an examination of the examples housed in the National Palace Museum. In Korea, in recent years, along with a surge in serious violent crimes, an increasing number of police have been killed or injured while on duty. Between 2017 and 2022, 2,301 police officers were injured in attacks by criminals (Korean police statistics, 2022). There is thus a clear need for protective gear, which can ensure the safety of police officers as well as ordinary citizens. In regard to the vests that police officers routinely wear while on duty, it is important that they are lightweight, easy to wear, and provide sufficient protection. Among these considerations, due to the dangerous nature of police work, the degree of protection provided is the most important. Traditionally, armor made of wood and metal has been used for personal protective equipment (Animesh & Abhijit, 2016). As both police officers and the public are highly exposed to the threat of stabbing with sharp weapons, stab-resistant protective equipment is gradually being introduced (Rodríguez-Millán et al., 2019) Against this background and with the aim of maintaining traditional techniques in a way that is appropriate to modern conditions, we considered that it would be of interest to investigate the application of modern high-tech protective materials to traditional armor structures. In this, we were inspired by the traditional *myeonpigap* [綿皮甲], which had a simple form and was made from inexpensive materials, with pigskin used for the anti-stab plate.

A buoyancy vest that can be inserted or detached from the buoyancy plate is described in Soo (2012). In this vest, metal plates are arranged side-by-side within the shield shell, while the front and rear shield plates overlap each other; however, this increases the weight and thickness of the vest. This method of inserting the shield plate inside the storage bag has the same drawbacks regardless of the size and shape of the plate. A fire-resistant riot suit that absorbs external impacts has also been developed (Cho, 2000). However, in this suit, flame-retardant and elastic materials, fabric, and an impact-resistant material (bamboo) are simply arranged in series, and no in-depth consideration of active and high-performance materials was given. Bullet-proof body armor in which scale-like ceramic tiles are attached to a fabric (Kevlar impregnated with a shear thickening fluid) using a stepped overlapping method was reported by Kim et. al. (2011). In this case, compared to armor with an integrated plate, the wearer's mobility is improved and the probability of penetration is lower. It is also possible to adjust the thickness of the armor covering each body part while still protecting the joints. Still, there are clear limits to the thickness due to the weight and price of the ceramic matrix composite (CMC). Body armor in which circular overlapping ceramic disks are enveloped between the flexible substrate and the fabric were described by Neal and Bain (2000). This armor performed poorly against bullets with a large inclination angle, and the stacking method used was found to have limitations.

Carbon composites are widely used where lightweight, high-strength materials are required, such as in high-performance cars, aircraft, and space applications (Ahmadi et al., 2019; An et al., 2021). Carbon composites have a density about 1/4 that of iron but are about 10 times stronger. Because of this, they are widely used in protective equipment such as helmets and sporting goods that need to be light but strong. Carbon composites have also been successfully used to make protective equipment such as police shields due to their excellent stab-resistant ability (Cheon et al., 2020). By using carbon composites as the protective material in body armor, improvements in the protective ability of the armor can be achieved along with a reduction in its weight. Although carbon fiber-reinforced plastic (CFRP) has been used as the structural material such as an exoskeleton, it has the disadvantage that, when used for general clothing, the ability of the wearer to carry out activities is greatly reduced. One of the advantages of exoskeletons made of carbon composite materials is that they are light weight and strong so can reduce the burden on the wearer's body. At the same time, in the clothing design point of view, carbon composite plates are made in a rigid form and difficult to follow the flexibility of the human body shape, so it is inconvenient to implement movements with a complex degree of freedom. In this study, the carbon panels were arranged in the form of scales, thus preserving the wearer's ability to move while maintaining the excellent mechanical strength of the material. This method of arranging the carbon panels also improves the wearer's safety because it produces a structure that is easy to graft onto clothes while at the same time creating armor with an increased protective ability that is convenient to wear. Not only is this study focused on comparison of protective performance of the armor-materials, but also the modernized reproduction of the old armor was presented with carbon composite panels.

Methods

Materials and manufacturing process

The carbon fiber composite was made of plain woven carbon fiber (CF) (T300-3k tow, 200 g/m^2, Toray Industries Inc.). Epoxy resin (YD-128), a curing agent (G-640), and an active diluting agent [butyl glycidyl ether (BGE)] were purchased from the Kukdo Chemical Co. Ltd. The resin and curing agent were mixed using a ratio of 100:72. The carbon composite was manufactured using a general vacuum-assisted resin transfer molding (VARTM) process (Fig. 1) as follows. Four layers of carbon fabric were stacked on top of each other; resin was then introduced through the inlet pipe and distributed through the flow media placed both on top of and under the carbon fabric. The resin was forced to impregnate the carbon fabrics, generating a through-thickness flow by the vacuum force.

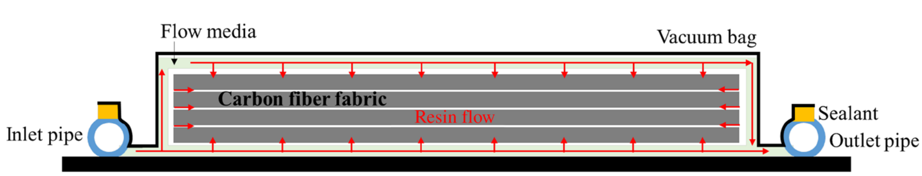

Fig. 1 Schematic of the VARTM (vacuum-assisted resin transfer molding) process

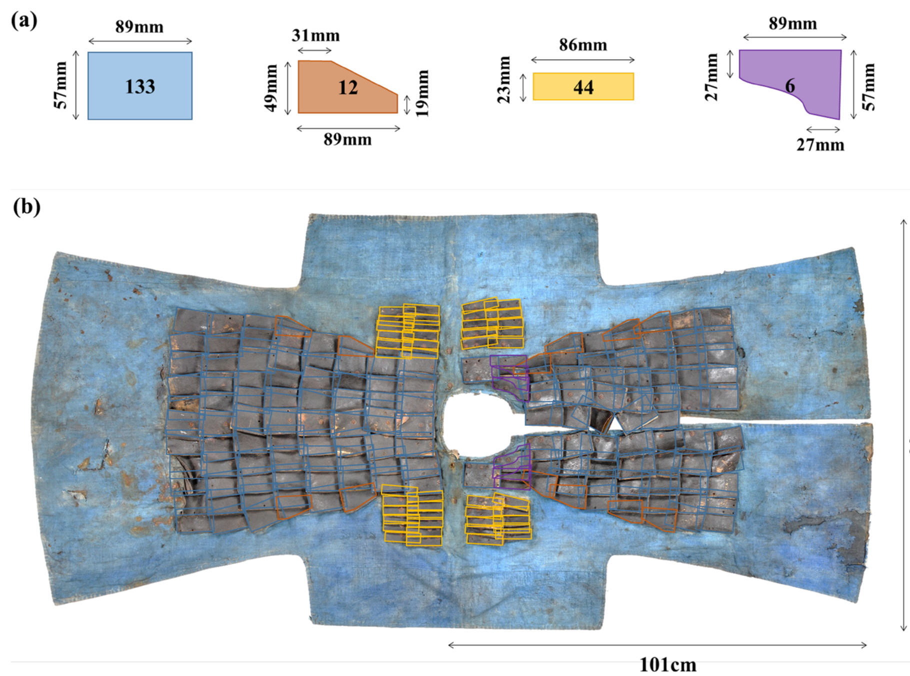

Fig. 2 **a** Panel dimensions (note: the number in the center of each example is the total number of panels of that type used in the armor). **b** Layout of panels in the armor (note: this armor is a collection of the National Palace Museum of Korea, and the photo is from the National Museum of Korea, in the public domain, https://www.gogung.go.kr/gogung/pgm/psgudMng/view.do?psgudSn=366570&menuNo=800065&gubunCd=&pageIndex=1&searchClCd=&searchCondition=&searchKeyword=%EB%A9%B4%ED%94%BC%EA%B0%91)

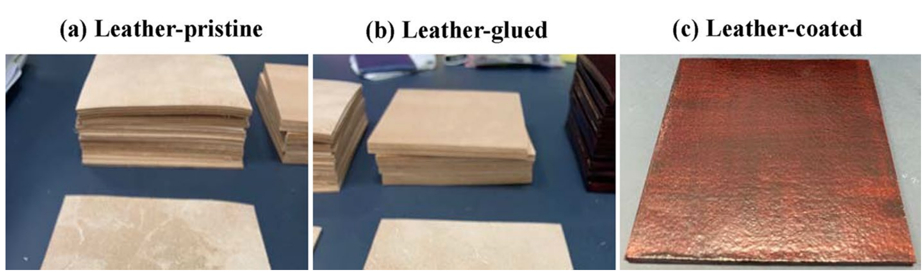

Fig. 3 Photographs of leather specimens: pristine (**a**), glued (**b**), and coated (**c**)

After 4 h of curing at 70 °C, the plate was cut using a waterjet cutting system (Superjet-T500, TOPS).

The carbon fabric that was produced had a thickness of 0.90 mm and was used to produce panels with dimensions that matched those of the ancient armor (see Fig. 2a, b). Most of the upper body part of the armor was covered with 133 (blue) basic panels that had dimensions of 89 × 57 mm. The sides (orange), shoulders (yellow), and clavicle (purple), were covered by 12, 44, and 6 panels, respectively; the shape and dimensions of each type of basic panel are shown in Fig. 2a. The total weight of the carbon panels was 1.2 kg, and the corner of each panel was rounded with 10R. A hole with a diameter of 3.5 mm was drilled in the center of each panel; the panels were then fixed in place using nickel rivets with a head diameter of 8 mm and a column diameter of 3 mm. The face (cotton/rayon blend) was padded with a cotton lining and stitched with no interfacing.

Leather specimens were also prepared according to the traditional method used to produce leather armor. As shown in Fig. 3, (a) Leather plates with dimensions of 100 × 100 mm were stacked on top of each other, and (b) glued together using the traditional natural glue *agyo* (阿膠), which is made from animal skin, muscle, and lipid. (c) Then, a coating of the natural material Lacquer (ott) was applied to the top and bottom surface of the leather plate using *ottchil* [漆]. Lacquer is derived from lacquer tree and is a well-known insect-repelling, antifungal, waterproof surface treatment. Lacquer coating was applied 2 times for raw lacquer and 3 times for refined lacquer, repeatedly.

Characterization

Low-velocity drop weight impact tests were conducted on specimens of CFRP according to the ASTM D7136 standard using a drop weight impact tester (Instron Dynatup 9350) (ASTM International, 2020). A hemispherical impactor tip with a diameter of 20 mm was used in these tests. The tests were conducted starting at an impact energy of 5 J; this was then increased in steps of 2.5 J until the specimen punctured. The specific impact energy (= impact energy per unit mass) and the penetration depth were measured at the maximum impact energy before puncturing occurred. Area density (= weight/area) was calculated to compensate for the thickness deviation. It was repeated at least three times and the average value was used. Photographs of the specimens and the reproduced leather armor were taken using a DSLR camera (EOS 800D, Canon, Japan).

Specimens of CFRP, stainless steel (SS), polycarbonate (PC), and reproduced "ancient" leather (cow skin) were also subjected to a stab resistance test performed using a drop tower impact testing machine (CEAST 9350, Instron, USA) based on the US National Institute of Justice (NIJ) standard 0115.00. Figure 4 shows the P1 blade impactor used in these tests and the test setup. The P1 blade had one cutting edge and was manufactured using BS4659 BO1 tool steel (West Yorkshire Steel Co. Ltd., UK) based on NIJ standards for stab resistance testing. The blade had a total length of 100 mm; the cutting edge of blade had a length of 33 mm and a thickness of 2 mm (see Fig. 4a). The specimens were placed on a supporting material consisting of four layers of neoprene sponge, each 6 mm thick, a single 30-mm layer of closed-cell polyethylene foam, and two 6-mm layers of rubber (see Fig. 4b). The total drop mass and the impact velocity used in the stab resistance tests were 2.437 kg and 1.81 m/s, respectively. The impact velocity, force, displacement, and energy were measured using the CEAST data acquisition system (DAS

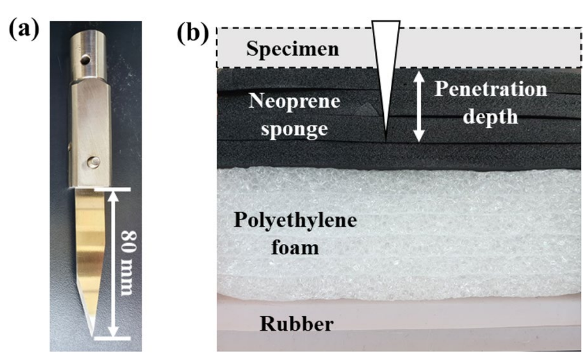

Fig. 4 P1 blade (**a**) and stab resistance test setup (**b**)

64K, Instron, U.S.A.), and the penetration depth was calculated from the time–displacement results. As shown in Fig. 2, different materials were tested at the same size of 100 × 100 mm, although they have different shapes depending on the location. Especially in real armor, there is a 5–10% overlap between the armors, which causes a slope on the surface of the panel. Although the incident energy is reduced by this angle of inclination, in this study, the drop weight and stab-resistance test was performed under vertical drop conditions in which the maximum energy is impacted.

Results and Discussion

Reproduced "ancient" armor

To produce a modern version of the traditional *myeonpigap* (綿皮甲) of the late Joseon Dynasty, the leather scales used in the *myeonpigap* (綿皮甲) were replaced with newly designed carbon composite panels while still utilizing the overall structure, size, and manufacturing principles of the leather armors of the late Joseon Dynasty. Other traditional elements of the armor that were preserved included the use of scales and the epaulettes. The cotton combat garment that is part of the *myeonpigap* (綿皮甲) is a cross-shaped structure when spread the front and back in flat. The front of the center, the seams of the sleeves, and the side seams of the *myeonpigap* (綿皮甲) can be opened and closed with buttons. The new carbon composite panels were designed based on the shape and size of the leather scales used in the *myeonpigap* examples housed in the National Palace Museum. The design of the epaulettes, which are included for both defense and balance, was also based on the three-segment structure of the museum artefacts. The leather scales of the traditional *myeonpigap* (綿皮甲) were restored to as close to their original condition as possible. According to the *Eoyeongcheonggusingnye* (御營廳舊式例) (Eoyeongcheong, 1707) and the *Hunguksaryechwaryo* (訓局事例撮要) (Hunlyeondogam, 1765), logs produced by the Royal Garrison Office and Military Training Agency of the Joseon Dynasty, to produce these scales, three layers of 1.5t pieces of cow leather were glued together with fish glue; lacquer was then applied to the scales a total of five times. We tested the ability of the restored leather scales to withstand impacts and compared this with that of the new carbon composite panels. Figure 5 shows a comparison between traditional armor (Fig. 5a) and the modernized version of the armor made using carbon composite panels (Fig. 5b). As can be seen from the Fig. 5b, the carbon composite panels are attached to the lining.

A prototype of a protective suit was produced by copying the basic shape of *pigap* (traditional Korean leather armor). A lightweight carbon composite material (thickness 0.9 mm, specific gravity 1.5) and high strength sword-proof performance was used to make the armor. The shape of the carbon panels was adapted for each body part after considering the needs of the wearer. To prevent penetration of the armor, a 5–10% overlap was allowed between panels. The design and construction of the armor and tests of its protective performance are described in detail in the next section.

Drop weight impact test Results

To assess the performance of the specimens in the drop weight impact tests, it was necessary to take into account both the weight and the impact resistance. Therefore, the

Fig. 5 **a** Example of traditional armor (the armor image is from the National Museum of Korea, in the public domain, https://www.gogung.go.kr/gogung/pgm/psgudMng/view.do?psgudSn=366570&menuNo=800065&gubunCd=&pageIndex=1&searchClCd=&searchCondition=&searchKeyword=%EB%A9%B4%ED%94%BC%EA%B0%91); **b** modernized version of the armor made using carbon compositepanels. Inset: planar view of the inside of the modern armor

results for the maximum specific impact energy (the maximum energy per unit mass) and the penetration depth were recorded. Two other areal density (50% less or 50% more) of specimens were compared in Table 1. In the case of the 0.53-mm specimens, the maximum specific impact energy is 25% higher than that for the specimens with a thickness of 0.90 mm. However, this is close to the impact energy of 5 J that results in penetration, so it seems that a substrate thicker than this is required for enough safety factor. In the case of the 1.49-mm specimens, the areal density is 50% greater than for the 0.90-mm specimens, and the maximum impact energy reaches to 17.5 J that is excessive in this purpose, so it is not recommended in the point of weight effectiveness (see Fig. 6). Therefore, these results suggest that a thickness of 0.90 mm would be appropriate. For this thickness, the energy absorbed per unit mass is 0.513 J/g and the maximum impact energy is 7.5 J, meaning that it should be possible to use this armor to defend against either an spike or a knife falling by 4.95 J (Lee et al., 2008).

Stab resistance test Results

The stab resistance test was performed on two different types of leather specimen: layers of pristine leather simply piled on top of each other, and layers of glued-together leather coated with lacquer on the top and bottom surfaces. The results are shown in Table 2. To imitate the original leather plates used in traditional armor, specimens with a thickness of about 5 mm were prepared. The pristine (non-coated) and coated

Table 1 Drop impact test for the carbon composite panel

Thickness (mm)	Areal density (g/cm^2)	Maximum impact energy (J)	Penetration depth (mm)	Specific impact energy (J/g)
0.53	0.08 ± 0.002	5.00	6.50 ± 0.29	0.64 ± 0.018
0.90	0.15 ± 0.003	7.50	8.20 ± 0.36	0.51 ± 0.014
1.49	0.22 ± 0.005	17.50	14.00 ± 0.62	0.78 ± 0.015

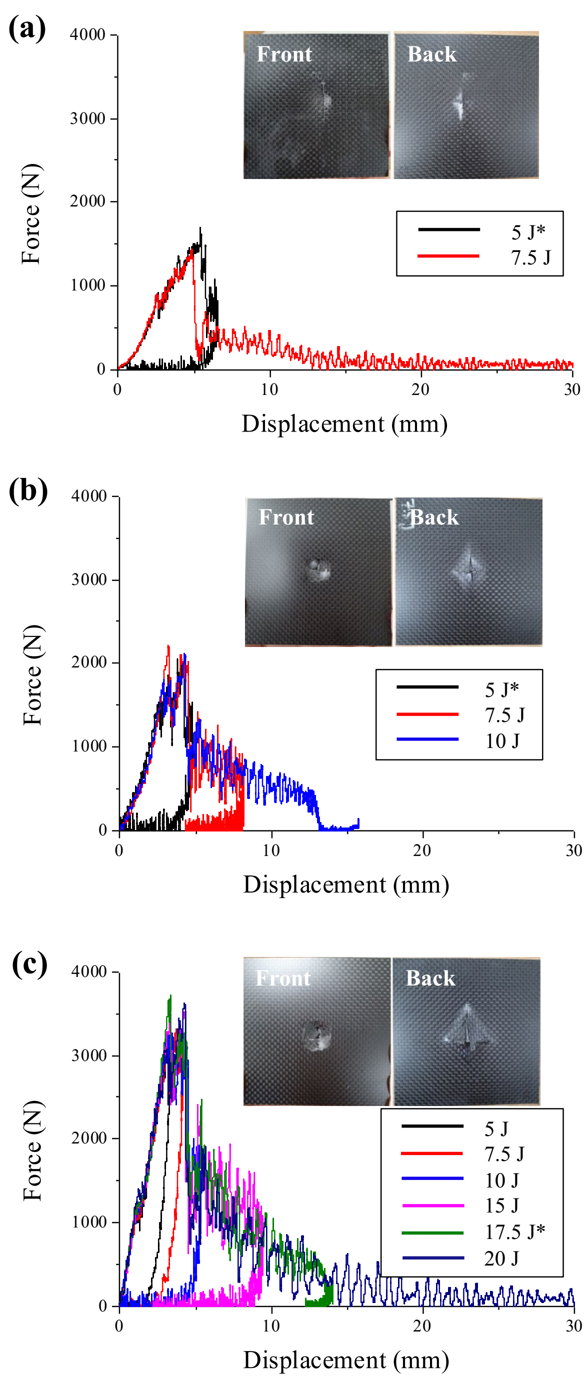

Fig. 6 Drop impact response of the carbon composite panel: thickness = 0.53 mm (**a**); thickness = 0.90 mm (**b**); and thickness = 1.49 mm (**c**). The maximum impact energy before puncturing occurred is indicated by a * in the legends. Inset: photographs of the front and back of each specimen at the maximum impact energy

leather specimens weighed 42.2 and 45.0 g, respectively (± 3.3% difference). As shown in Fig. 7a, the displacement proceeded before 50 mm for the coated leather specimen, whereas it reached to more than 50 mm in the case of the pristine leather specimen. The results for the maximum force also show that a greater resistive force was

Table 2 Stab resistance test for an impact energy of 4 J

	Density (ρ, g/cm^3)	Thickness (mm)	Maximum force (N)	Penetration depth (mm)
Leather (pristine)	0.803	5.26	167.3	13.27 ± 0.66
Leather (coated)	0.844	5.34	185.9	3.77 ± 0.18
PC	1.197	1.19	172.6	12.90 ± 0.65
SS	7.593	0.20	195.9	9.02 ± 0.45
CFRP	1.547	0.90	252.2	3.31 ± 0.16

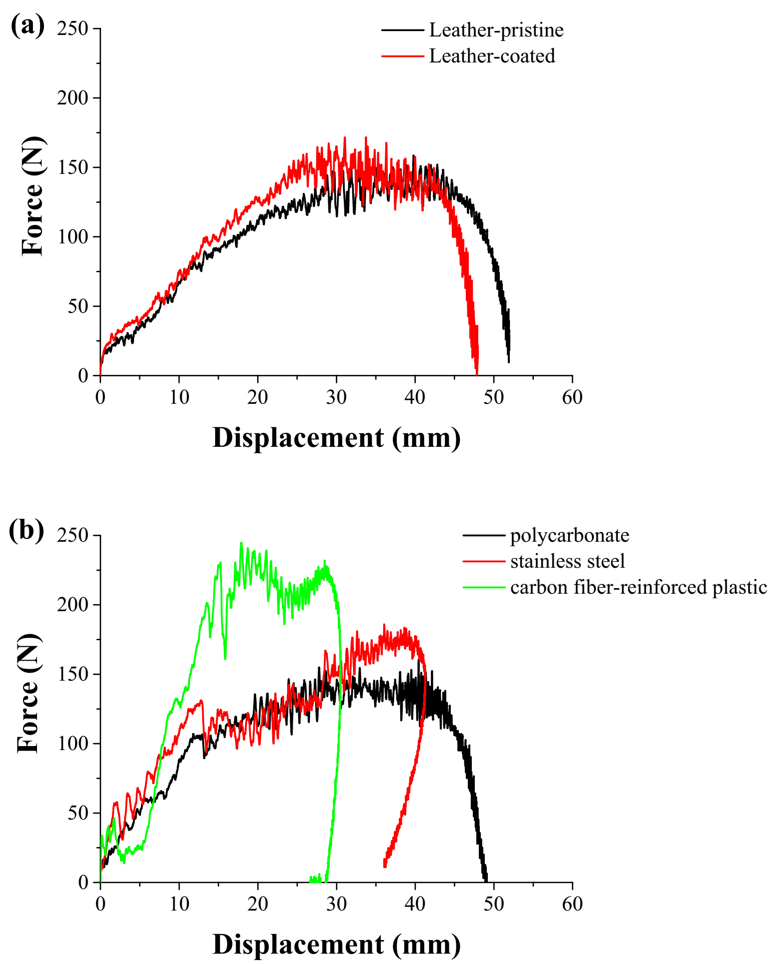

Fig. 7 Results of the stab resistance test: force–displacement curves for an impact energy of 4 J for leather (**a**) and PC (polycarbonate), SS (stainless steel), and CFRP (carbon fiber-reinforced plastic) (**b**)

provided by the coated leather specimen than the pristine one. Surprisingly, the application of the glue and coating reduced the penetration depth dramatically from 13.27 to 3.77 mm (see Table 2). According to the NIJ standards, it is suggested that 7 mm is the critical depth at which damage to the human body can result. Thus, these results show that the traditional leather armor (represented by the coated specimen) performs effectively in this respect.

The stab resistance performance of PC, SS, and CFRP was also investigated for comparison. PC and SS plates of the same mass as the CFRP used in Fig. 6b were tested; thus the thicknesses of the PC, SS, and CFRP specimens were 1.2, 0.2, and 1.0 mm, respectively; the corresponding masses were 14.1 g, 15.1 g, and 15.4 g (±5% difference), respectively. As can be seen from Fig. 7b, it is clear that the CFRP panel has greater resistance to penetration by a blade than PC or SS. The penetration depth is 3.31 mm for CFRP whereas for PC and SS, it is 12.90 and 9.02 mm, respectively. High-strength carbon fiber and composite materials made from this are known to be good anti-stab materials; however, these results show that CFRP performs even better than a sample of steel of the same mass.

Conclusions

Inspired by the Korean traditional *myeonpigap*, which has a simple shape and is made of inexpensive materials, we used stainless steel (SS), polycarbonate (PC) and lacquer-coated leather (cow skin) specimens. In particular, leather specimens were produced using a manufacturing method that imitated that of traditional armor. A 0.9-mm-thick panel was tested for weight and impact resistance. It was found that this panel could absorb 0.51 J/g and a maximum impact energy of 7.5 J, meaning that it would be able to protect against spikes and knives falling by 4.95 J. High-strength carbon fiber composites are known to be excellent puncture-resistant materials; however, it was found that a leather specimen proved superior stab resistance in this respect. Surprisingly, the penetration depth for this leather specimen was found to be only 3.77 mm. NIJ standards suggest that 7 mm is the depth at which injury to the human body can occur. The lacquer-coated leather specimens reproduced according to the traditional method confirmed a high level of protective performance. By combining the convenient structure of old armor with the light weight of high-tech materials, it was possible to attain a balance between traditional and modern fabrication methods. Therefore, conventional armor skin plates (coated specimens) can be considered to have an effective stab-resistance performance. In addition, by examining modern materials together, it was considered that the convenient structure and performance of traditional armor could be used practically. In this way, it was successfully proved that the practical needs of modern wearers can be combined with tradition. Although it has been hundreds of years passed, the state-of-the-art technology that was available at the time was condensed in the old armor. At this point, there is a mission given to us to correctly interpret the tradition in the history and inherit it today.

Acknowledgements
Not applicable.

Authors' contributions
JH developed the research idea. TK performed mechanical analysis and collected the data. GYP and MWL were major contributor in writing the manuscript. All authors read and approved the final manuscript.

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Funding
This work was supported by the Police-lab 2.0 Program (www.kipot.or.kr) funded by the Korean Ministry of Science and ICT (MSIT, Korea) and the Korean National Police Agency (KNPA, Korea) [Project name: Development of a next-generation police vest; Project number: 220122M04]

Availability of data and materials
The data used 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.

Received: 28 February 2023 Accepted: 22 April 2023
Published online: 05 August 2023

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