ウェアラブル・クッション製品のための 3D ニット複合材の開発

Development of a 3D-shaped knitted composite for wearable cushioned products

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Abstract

Wearable cushioned products are important to protect human bodies during sports or work. Cushioning paddings made of elastomeric materials such as ethylene-vinyl acetate (EVA) foam, expanded polyethene, etc., are adopted to absorb impact forces. The paddings are usually inelastic, which could be challenging to fit the movement of knee joints and lead to displacement. In this study, a new knitted composite which consists of soft surface layers made of yarn, a shock absorption middle layer made of monofilament and silicone inlays and additional elastic inlays on the surface for forming curvature was developed. The knitted composite was further developed into a knee padding. A 3D image analysis study was conducted to understand the knee shape, skin strain and contour variation during bending motion. Based on the knee morphology, a 3D padding sample was directly knitted from yarn and materials. The air permeability and mechanical properties of the new padding were evaluated and compared with a conventional spacer fabric and a commercial EVA padding product. The results showed that the new padding could have much better air permeability and extensibility than EVA, which can facilitate breathability and address joint motions. The new padding with silicone inlay can provide better impact force absorption with a lower thickness than spacer fabric. The outcomes can provide a good reference for the development of cushioning materials by knitting method.

1. Introduction

Cushioning garments such as orthopaedic supports, protective paddings and orthotic insoles are used on sports and medical basis to protect and support human bodies. They are usually made of elastomeric materials, such as thermoplastic foams or chloroprene rubber, combined with fabrics to absorb impact forces. In order to fit the contours of body parts and provide enough support and impact force absorption, the materials were trimmed, sewn and laminated to the desired shape. In the production process, a large amount of resources is consumed and a huge volume of waste is created. The thick and rigid cushioning materials would hinder the joint motions for the protective padding applied on the body parts with a high range of motions such as knees or elbows. The inelastic padding fails to address the variation in skin strain during motions, leading to slippage, displacement and discomfort. The non-breathable thermoplastic foams and chloroprene rubber also inhibit the wearing comfort of the cushioning garments.

This study aims to develop a 3D-shaped sandwich material by knitting for body protection. The material would be soft and flexible to fit the body contour and would not limit the range of motion of joints; have good air-permeability to improve wearing comfort; and can absorb impact force well to give sufficient protection to the body. With the large range and complexity of joint motions, it is challenging to develop a comfortable knee padding. Therefore, this study would investigate the feasibility of improving the knee brace by using the proposed composite structure. Besides, the padding would be directly made from yarns to the desired 3D shape of the knee padding to minimize waste and shorten the production process.

2. Methodology

2.1 Understanding the dynamic morphology of knees

A hand-held three-dimension (3D) body scanner (EinScan H, shinning 3D, China) was adopted to take the 3D images of knees to obtain important information on knee contours and change of skin strain for the development of knee brace and knee padding. 50 Asian males (age: 26.1±1.6, height 174 ±7.3 and weight 67.3±12.7) were invited for the 3D scanning. Four 3D images of the right knees were obtained with bending angles of 0°, 30°, 60° and 90° for each participant (Fig. 1). The experiment was approved by the Human Subjects Ethics Committee of the Kyoto Institute of Technology and a written consent was obtained from each participant prior to the start of the experiment.

The 3D scanned images were then imported to a 3D scan software (M-soft, Techmed 3D, Canada) for obtaining the different length and circumferential dimensions of knees. The variations in the dimensions, skin strain, asymmetry and side shifting of the patella under different bending angles were evaluated.

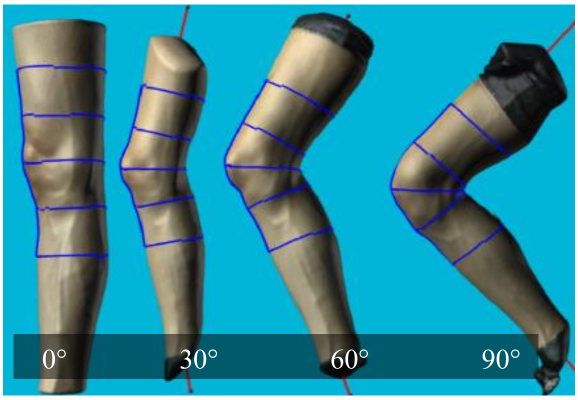

Fig. 1. 3D image of a knee at four bending angles

2.2 Development of 3D-shaped knitted composite padding for knee brace

A novel padding with high cushioning ability and curvature fit to the body contour was developed directly from yarn by a weft knitting machine (SWG091N210G, Shima Seiki, Japan). The padding is a three-layer structured fabric (Fig. 2). The two outer layers forming a jersey structure provide air permeability. The inner layer in touch with the skin was inlaid with elastic yarn and had less number of courses than the outer layer to form an imbalance curve structure to match the knee contour obtained from the 3D scanning. Similar to conventional spacer fabric, the middle layer consisted of monofilament yarns forming tuck and miss stitches to support the structure and provide cushioning. Additional silicone hollow tube was inlaid to the middle layer to provide extra support and enhance the shock absorption and cushioning performance. A knee padding sample was produced by using 450D polyester draw textured yarn to form the surface and polyamide monofilament with a diameter of 0.14mm as the connective yarn with a silicone hollow tube of 1mm in diameter as the inlaid.

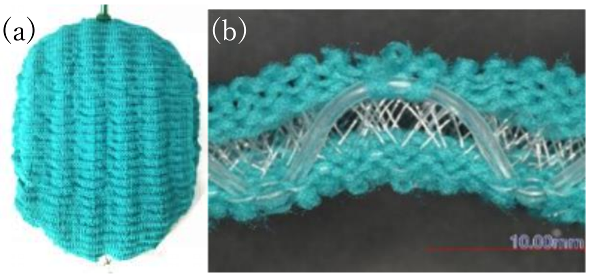

Fig. 2. (a) The 3D-shaped knitted padding and (b) its course-wise cross-sectional view

2.3 Properties evaluation

The properties of the developed knitted padding were evaluated and compared with a knitted spacer fabric padding with the same materials, shape and curvature but without the silicone tube inlaid and a commercial knee padding sample made of Ethylene-vinyl acetate (EVA). The air resistance of the three samples was tested by an air permeability tester (KES-F8, Kato Tech Co., Ltd, Japan) under the standard testing condition with an air vent area of 6.281cm^2 and air volume of 2cm/s. A tensile test was carried out to test the extensibility of the samples by a universal testing instrument (EZ-X Compact Tabletop Tester, Shimadzu, Japan). The gauge length was 135mm and the clamping width was 40mm. The samples were extended at a speed of 100mm/min and up to a strain of 22% which is the change of skin strain when knee bending from standing straight to 90°. The compression property was measured by a compression tester (KES-G5, Kato Tech Co., Ltd., Japan) with a circular testing area of 2cm^2 at a compression speed of 0.2mm/sec and maximum stress of 49kPa. The impact force absorption property of the samples was evaluated by a set-up of a ball dropping test using a 63g metal ball dropped from a distance of 10cm.

3. Results and Discussion

3.1 Knee dimensions variation at dynamic motions

From the 3D image analysis, significant variations due to the change of bending angles are found on the leg circumference at the centre of the patella, 7.5cm above and 15cm below the centre of the patella, while the variation is not significant at 15cm above and 7.5cm below the centre patella.

Two length measurements were measured along the centre front of the knee from the center of the patella vertically to 15cm above (Lgth_OH) and to 15cm below (Lgth_OL) at a bending angle of 0°. It is observed that there is a linear increment of Lgth_OH and Lgth_OL by 24.8% and 20.3%, respectively, when reaching the bending angle of 90° (Fig. 3). Besides, the vertical length of the patella increased by 19% with the bending angle increasing from 0° to 90°. This shows that the deformation of the patella account for most of the deformations observed in Lgth_OH and Lgth_OL.

By looking at the contour, the knee is not symmetrical in shape, with a steeper curvature on the right side and a more gradual curvature on the left side. The patella is found to be closer to the lateral side than the medial side of the leg, and the side shifting accentuates when the knee bends from 0° to 90°.

These findings of knee morphology act as a reference for the development of knee brace and provide guidelines for the position, shape and form of knee padding.

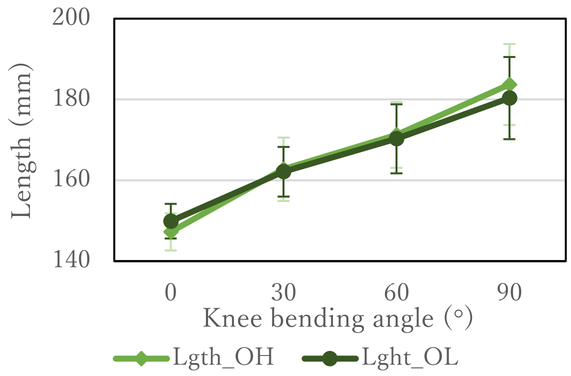

Fig. 3 Change of leg lengths at different knee bending angles

3.2 Properties of the developed knitted composite

Fig. 4 shows the thickness and air permeability of the three samples. With the silicone inlaid, additional connective force is given, pushing the two surface layers closer together and leading to a thinner sample compared with the spacer fabric without the inlaid. Both composite padding and spacer fabric padding have very low air resistance. The silicone inlaid does not significantly affect the air resistance. On the other hand, EVA is barely air permeable and fails to be measured by the tester. This shows that the composite padding can allow better air permeability than the commercial EVA product.

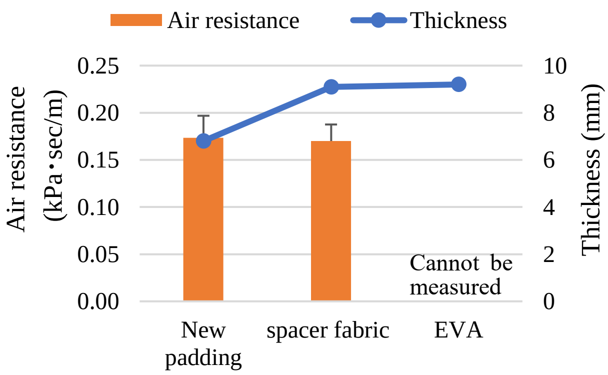

Fig 4. Thickness and air resistance of the samples

The tensile strength of the samples is presented in Fig. 5. Adding silicone inlay, giving a thinner fabric, does not bring a significant change to the tensile stress-strain behaviour. The commercial padding is not able to extend to 22% and can only be extended to 5% with a tensile strength of 10N. Both new padding and spacer fabric samples made by knitting have better extensibility to facilitate body motions.

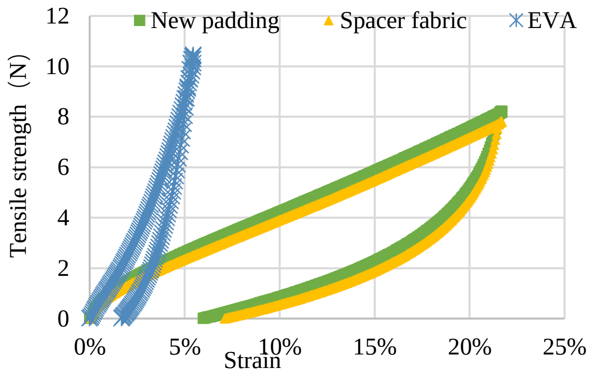

Fig. 5. Tensile strength of the samples

From the compression stress-strain curves of the samples (Fig. 6), the two knitted samples are easier to be compressed than the EVA padding. The new composite padding is the easiest to be compressed amongst the three samples. Adding silicone inlaid to the curve fabric sample can affect the connective monofilament yarn and bring a softer and easily compressed structure. When the compression strain is above 60%, the slope of the stress-strain curve largely increases. This showed that the silicone tube brings extra support against further collapsing of the padding.

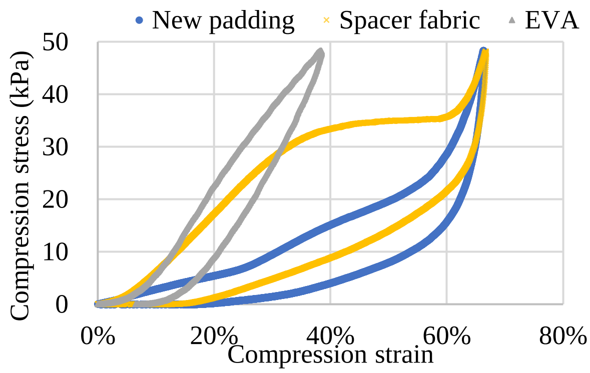

Fig. 6. Compression curves of the samples

The ability to reduce the impact force can be shown by the force-time curves obtained from the ball-dropping test (Fig. 7). Although the knitted samples cannot provide impact force absorption as well as EVA, the new padding can reduce a larger amount of impact force than the spacer fabric. The silicone inlay allows a thinner knitted padding to absorb a larger amount of impact force. However, further investigations on the fabric structure and increment of fabric layer are suggested to achieve the impact force reduction performance comparable to elastomeric padding products.

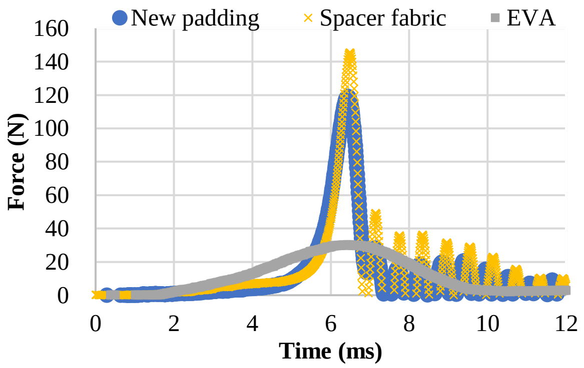

Fig. 7. Impact force-time curves of the samples

4. Conclusion

The present study developed a new knitted structure to provide cushioning. With the use of a whole garment knitting machine, the 3D shape and the curvature of a protective padding can be directly produced from yarn. As no further cutting and trimming are needed, the number of processing wastes can be reduced. This production method is a relatively green process that can reduce the carbon footprint and energy consumption.

The new knitted padding is a composite of soft surface yarns and shock absorption silicone inlays, elastic yarns and connective monofilament yarns. Based on the knee morphology and dimension variation caused by knee motions obtained from 3D image analysis, a padding with the desired contour to fit on the knees can be produced.

Traditional elastomeric padding materials are barely air-permeable and have poor breathability. The sandwich-knitted structure retains the properties of the weft-knitted fabric, such as soft hand feels and good air permeability. Besides, the knitted padding has better extensibility to address the joint motions and thus reduces the displacement of padding during body movement.

Comparing with a conventional spacer fabric, better impact force absorption can be achieved by a thinner knitted silicone inlaid composite which is a great improvement on 3D knitted fabric to be used for cushioning. Further study will be carried out to investigate the fabric structure and composition parameters to enhance the impact force absorption function.

Acknowledgements

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Presentation of research results

Pierre RINGENBACH, Yijia ZHANG and Annie YU. (2022) Using 3D scanning to study knee shape deformation under motion. The 49th Textile Research Symposium.

Annie YU and Yijia ZHANG. (2023) Development of a Wearable Knee Protector by Novel Knitting Spacer Fabric. The 16th Textile Bioengineering and Informatics Symposium.