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Preparation of the polyester/cotton composite yarn with alternating segmented structure and interval color via a promising physical spinning approach

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Abstract

Herein, a novel kind of composite yarn with alternating segmented structure and interval color has been prepared based on a ring spinning approach. By adjusting the relative motion and blend ratio of the colored polyester filament and natural cotton staple fiber in yarn spinning process, a series of composite yarns were designed and prepared with various segmented structure and cyclical change of the distinct colors. The blend ratio was found to strongly influence on the segment frequency and yarn performance, achieving an improved mechanical property and yarn performance. A color systematic analysis indicated that the combination of alternating structural change induced interval color sense and gradient at the merged regions would lead to an enhanced stereoscopic visual effect of the composite yarns. Moreover, the composite yarns were confirmed to have an excellent weavability and able to endow different patterns and visual effects to the textiles. Thus, considering of the above advantages and multifunctionalities, this work should spur great possibilities for dyeing industry with the promising physical spinning method.

Keywords: Color analysis, Segmented structure, Interval color, Composite yarn, Ring spinning

Introduction

With the rapid development of the economy and society, more complex requirements for the fashion textiles have been put forwarded in recent decades. Besides the traditional fabric, diversity of dyed yarns for the fashion sense has received much attentions due to its extensive potential applications and huge global market. Therefore, more researchers are focusing on the various technologies for the colorful yarns' construction (Wang et al. 2019). Specifically, the traditional color yarn spinning is usually dyed the fiber first, and then mixed two or more fibers aiming to confer the textiles with designed colorful visualizations (Kim and Jeon 2014). However, for dyeing process, the fiber treatment conditions (e.g. acid, alkali, high temperature etc.) would strongly affect the fabric performance and the use of dyeing materials that are harmful to the human being and environment. Moreover, the removal of wax, grease, glue and other substances contained in fibers often leads to a decrease of the polymerization degree, lower mechanical strength and poor spinnability after the dyeing processes (Venkatraman and Liauw 2018). The dyeing auxiliaries used in the fiber dyeing process are diverse, resulting in complex pollutant components, large fluctuations of acidity and alkalinity in wastewater. Thus, a physical dyeing method that avoid the use of toxic inorganic reagents is highly desirable for the fashion textile industry.

Generally, the composite yarns that composed of multifilament and staple fiber have been considered as the most promising support materials to meet the increasing requirements (Aier et al. 2009). Due to their obvious advantages of combining the structures and functions originated from each component, the composite yarns showed potential for widespread application of fashion textiles (Wang et al. 2020; Wei et al. 2017). In decades, various novel composite spinning technologies have been developed to obtain the new style and high-quality composite yarns, such as the corefil, sirofil, staple and embeddable/locatable spinning (Chi et al. 2012; Naeem et al. 2014; Soltani and Johari 2012; Tehran et al. 2011; Xia and Weilin 2013). Despite above effective methods are possible to confer spun yarns with high quality in some cases, the monotone structure and appearance for resultant composite spun yarns in the longitude and cross-section missing the fancy effect to produce new style fashionable and high-quality fabrics (Wickramasinghe and Foster 2014; Xia et al. 2018). Thus, above findings motivate us to develop a green and facile method to prepare the multi-functional composite yarns with high quality and mechanical properties based on the current ring spinning technologies (Hajiani et al. 2014).

Herein, a novel kind of composite yarn with alternating segmented structure and interval color has been prepared under a ring spinning method by using the colored polyester filament and natural cotton staple fiber as the raw materials. By regulating the spinning process, a series of composite yarns with varied segmented structure have been successfully designed and prepared, and which exhibited unique interval color patterns and stereoscopic visual effect. The blend ratio of the colored polyester filament and natural cotton staple fiber could significantly affect the cyclic interval color. In which, the coloration characteristics of the composite yarn with varied interval color were investigated in this work. Additionally, the influences of blend ratio on mechanical properties, visual execution and characteristic performances of the composite yarns (e.g. hairiness, unevenness, linear density) have been systematical investigated. Moreover, the composite yarns were knitted into the textiles with different dimensional structures. To verify the versatility, several kinds of the colored polyester filaments produced by adding masterbatch in the melting process have been used to "dye" the natural pure cotton fiber to achieve different interval color effects. In summary, we believe this physical color matching method would provide a new perspective for the green dyeing technology.

Methods

Production of polyester-cotton composite yarn with interval color

The polyester/cotton composite yarn with segmented structure is prepared via a controllable ring spinning process. The 80D/36F colored polyester filaments and 6.0 g/10.0 m natural pure cotton rovings used in this work are purchased from Yangzhou Jinhui

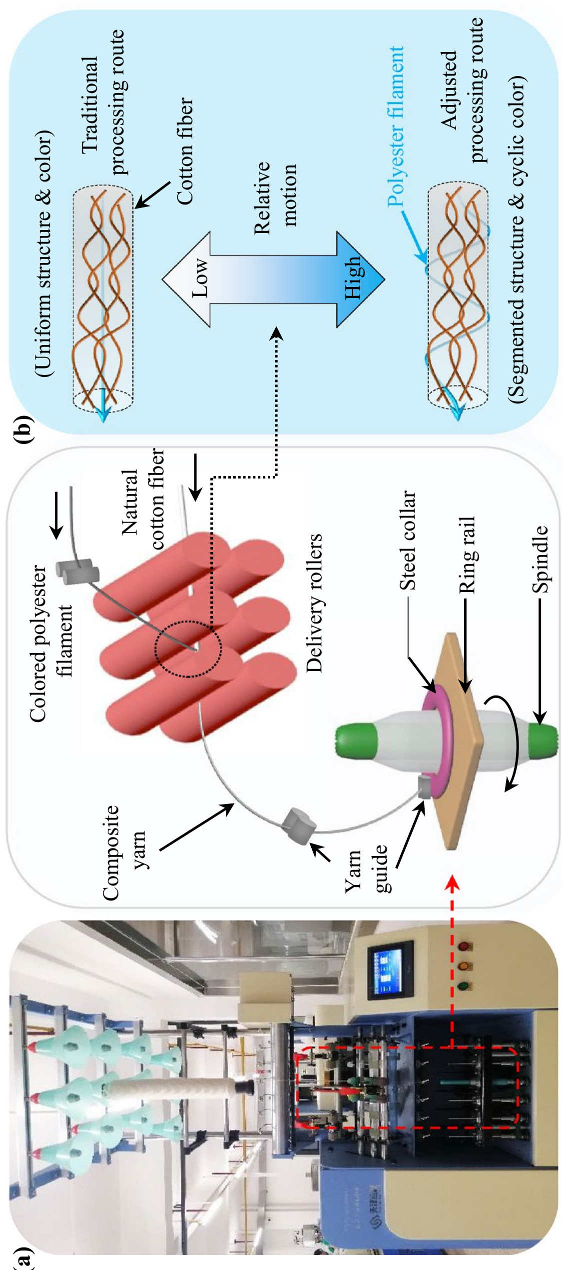

Fig. 1 **a** Experimental setups and schematic diagram of the ring spinning process. **b** Proposed mechanisms for the relative motion induced structural changes of the composite yarns

Chemical Fiber Co., Ltd. and Jiangsu Yiren Textile Technology Co., Ltd. respectively. The instrument for composite yarn preparation and corresponding spinning process is schematically illustrated in Fig. 1a. The conventional ring spinning frame with a drafting system was applied to produce the composite yarns. Detailed parameters for the composite yarn preparation are as follows: twist multiplier 380; back drafting ratio 1.5; filament pretension 15 cN. The reason for the spinning settings is to secure effective spinning without bad drafting and excessively large or small spinning balloons. Specifically, the flexible polyester filaments were blent with drafting cotton roving and then being twisted to form the composite yarns. The filaments fed position was fixed at the center of the cotton roving. By controlling relative motion of the two components, the raw materials were expected to obtain a polyester/cotton composite yarn with a novel segmented structure and interval color sense in the longitudinal structure (Fig. 1b). To provide the direct explanation, a high-speed camera (PhantomVEO 440, Vision Research Co., Ltd.) has been used to achieve the real-time recording of the relative motion. We collected some images from the videos (note: see Additional files 1, 2) and the results are showed in Additional file 3: Fig. S1. Compared to the traditional spinning approach, we could find that there is a large relative motion between the polyester and cotton staple fiber during the spinning processes (Additional file 3: Fig. S2). These behaviors presumably could be explained by the inner and outer transfer movement of colored polyester filament within the cotton staple fiber as compared to the yarns prepared via the traditional spinning route. Further evidences for the composite yarn formation are provided in the following sections.

Characterizations

The linear density was calculated by weighting the YG (B) 086 yarn with a certain length. The yarn length was measured by using the machined provided by Wenzhou Darong Textile Instrument Co., Ltd. The yarn strength was tested by the YG (B)021DX electronic single yarn strength instrument (Wenzhou Darong Textile Instrument Co., Ltd.) with a testing speed of 400 mm/min. The hairiness distribution of the 10 m yarn was carried out by a YG173A yarn hairiness tester (Suzhou Changfeng Co., Ltd.) with the testing rate of 30 m/min. The unevenness of the samples were conducted by a YG133B/M evenness tester (Suzhou Changfeng Co., Ltd.) with the testing rate of 300/min. The longitudinal and cross-sectional structures of yarn and fabric were observed by a VHX-5000 ultra-depth 3D digital microscope (Keyence Co., Ltd.). The X-rite COLOR i7 spectrophotometer (X-rite Co., Ltd. UK) was used to reveal the colorimetric properties and spectral reflectance of yarn samples. The microstructural image was recorded by using a scanning electron microscope (SEM; VEGA3 LMU, TESCAN). All the composite yarn samples were stored for at least 1 day under a standard atmospheric condition (60% relative humidity and 20 °C).

Results and discussion

Structural appearance of the segmented yarns

In the first section we demonstrated the segmented structure can be finely regulated by varying the blend ratio of composite yarn. Initially, for sharp contrast, the black polyester filament and white natural cotton roving were used as the two raw materials. A

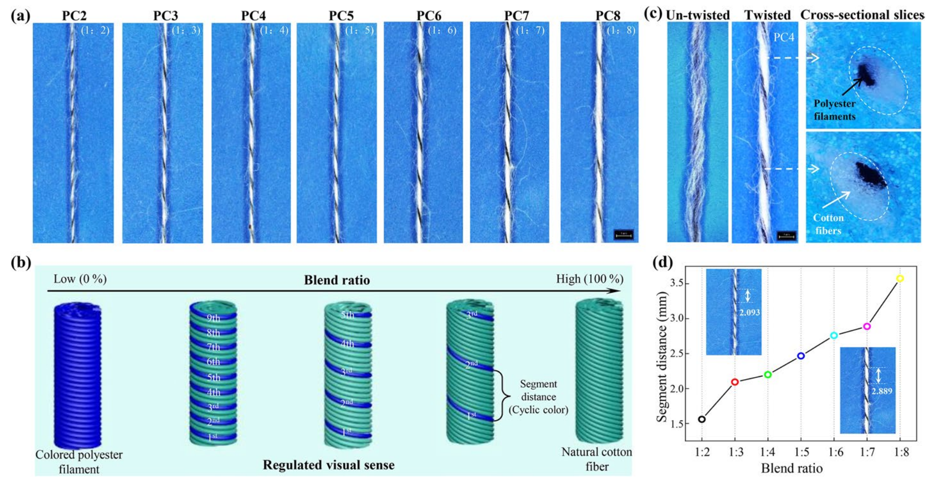

Fig. 2 **a** Optical images of the composite yarns prepared with varied blend ratios. **b** Schematic illustration of the blend ratios induced structural changes and regulated visual sense. **c** Optical observations of the segmented structure at different twisted states and regions. **d** Segment distance as a function of bending ratios

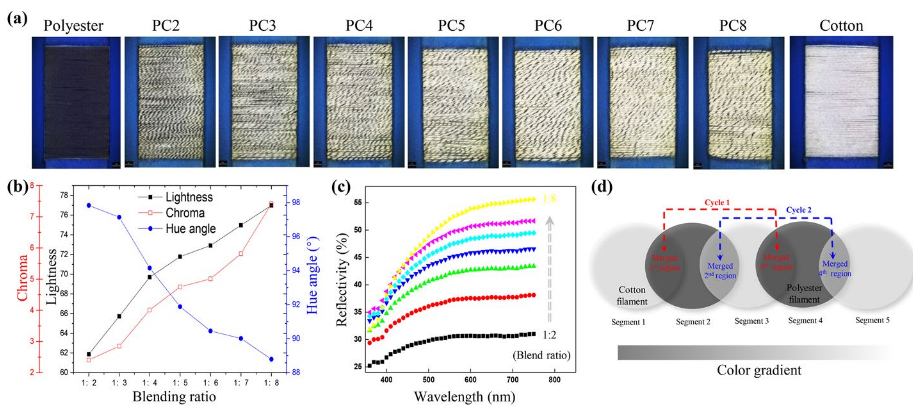

Fig. 3 **a** Optical observations of the segmented yarns wrapped on glass slides. **b** Lightness, chroma and hue angle measurements of the composite yarns. **c** Blend ratio induced changes of reflectivity. **d** Schematic analysis of interval color sense and gradient

series of composite yarns have been fabricated with the blend ratios ranging from 1:2 to 1:8 and the resulted yarns were coded as PC2 ~ PC8, respectively. The pure samples were provided as the controls. For optical observation, the yarns were fixed under an ultra-depth 3D digital microscope and imaged by using the attached digital camera. As showed in Fig. 1a, all the yarns have fewer surface hairs and been tightly twisted with novel segmented structure and changing distances. The number of intervals collected from 1 cm per unit length were showed in Additional file 3: Fig. S3, and from which a negative relationship could be observed between the segment frequency and blend ratio. The possible large motion induced structural changes have been schematically illustrated in Fig. 2b. By increasing blend ratio (i.e. cotton content), the composite yarns were expected to have various segment distance and cyclic color sense. In order to further study the surface microstructure, the yarn was cut into small pieces, sprayed with gold and then photographed by using a scanning electron microcopy. The tightly coupled two filaments at different regions were clearly observed indicating the composite yarn has an alternating segmented structure (Additional file 3: Fig. S4). Particularly, for the cross-sectional observation, a simple embedding method has been employed for the yarn slices preparation. The pictures in Fig. 2c were collected at different twisted states (e.g. front views) and segment regions (e.g. cross-section views). From the twisted state, the polyester filaments and cotton staple fiber were observed to have the unique segmented structure in the composite yarns. Surprisingly, from the un-twisted state, the black polyester filaments were found to be embedded in the cotton yarn with loose structure. These results indicated the polyester filaments were somehow unevenly distributed within the cotton yarn and provided a strong evidence for the unique blend mode that was dramatically different compared to the sirofil yarns (Liu et al. 2007), and such oscillating embedded states can be further confirmed by the cross-sectional observations at different regions. Thus, it can be concluded that the black polyester filament has a large relative motion to the cotton staple fiber, causing the inter- and outer-movement within the yarns and exhibiting cyclic color sense. These color changes could be attributed to the higher relative motion of the two components during the twisted processing procedure, leading to a partially interpenetration at their interface (Chi et al. 2012). Moreover, the cyclic segmented structure can be tailored by changing the blend ratios with the segment distances ranged from 1.559 mm to 3.576 mm (Fig. 2d).

Color analysis of the segmented yarns

Next, we investigated the visual effects of the composite yarns with various segmented structures. For a systematic analysis, all the yarns were firstly wrapped on each glass slide with same area of 2.5 cm × 4 cm. The pure cotton yarns and polyester filaments were served as controls. By increasing the blend ratios, the composite yarns showed a tendency to be brighter as the actual appearance gradually changed from gray dark to the lighter state (Fig. 3a). In order to further study of the chromatic characteristics of composite yarns, three elements including lightness, saturation and hue values have been evaluated. Specifically, a spectrophotometer (X-rite colori7) has been employed to reveal the colorimetric properties and spectral reflectance of yarn samples, and the results are as showed in Fig. 3b and c, respectively. Interestingly, it could be found that both of the lightness and saturation values were increased with the increasing content of natural cotton fibers in the composite yarns. On the contrary, the hue angle values were gradually decreased with the increased of blend ratio. These results could possibly be explained by the changes of radial distributions of these two components during yarn spinning process and the strong diffusion reflection origins from the natural cotton staple fibers. Actually, a similar result has also been observed from the spectral reflectance measurements. The typical PC8 sample fabricated at a relatively large blend ratio (e.g. 1:8) exhibited a strong backscattering effect at the yarn surface layer as confirmed by the quantitative color analysis in Fig. 3c. These results demonstrated that the higher white cotton staple fiber content presumably will lead to a lower segment frequency, higher reflectance value and cyclic color sense at each segment region (e.g. changed from dark

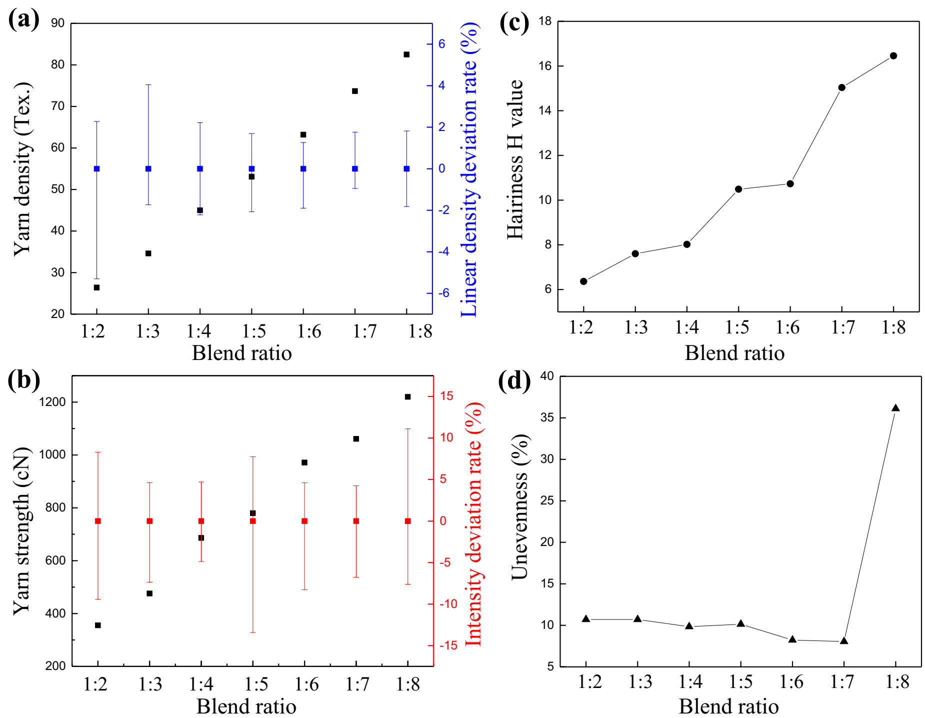

Fig. 4 **a** Yarn density, **b** Hairiness, **c** Yarn strength and **d** Unevenness of the composite yarns prepared with different blend ratios

gray to light gray). Figure 3d gives a simplified explanation of the structural changes induced color gradient in the composite yarns. Specifically, the segmented structure and cyclic merged regions were expected to endow a complex synergistic visual effect on the yarns and the similar behaviors for color coordination has also been revealed by the other groups (Yang et al. 2019). The color cycle is composed of a pure colored polyester segment and adjacent merged region (e.g. superposition of the polyester filaments and pure cotton fibers). Thus, we believe this work would provide the great possibilities for the multi-colorful composite yarns assemblies just by spinning of the composite yarns with two or more colored components and segmented structures.

Mechanical properties and yarn performances

It is known that, besides the visual sense, the mechanical properties, hairiness and other comprehensive performance indexes of the composite yarns are the main points needed to be further considered for their practical applications (Yong et al. 2019). Therefore, the influences of blend ratios on the mechanical properties and yarn properties were discussed in this section. Since feeding amount of colored polyester filament used in this work is fixed, it is reasonably to find the composite yarn fabricated at a higher blend ratio will process more cotton fibers but less polyester filaments. As showed in Fig. 4a, the yarn density displayed a linearly relationship and smaller deviation rate with the blend ratio. By increasing the cotton content, the higher hairiness value and yarn strength could be found in Fig. 4b, c, respectively. The yarn strength was observed to gradually

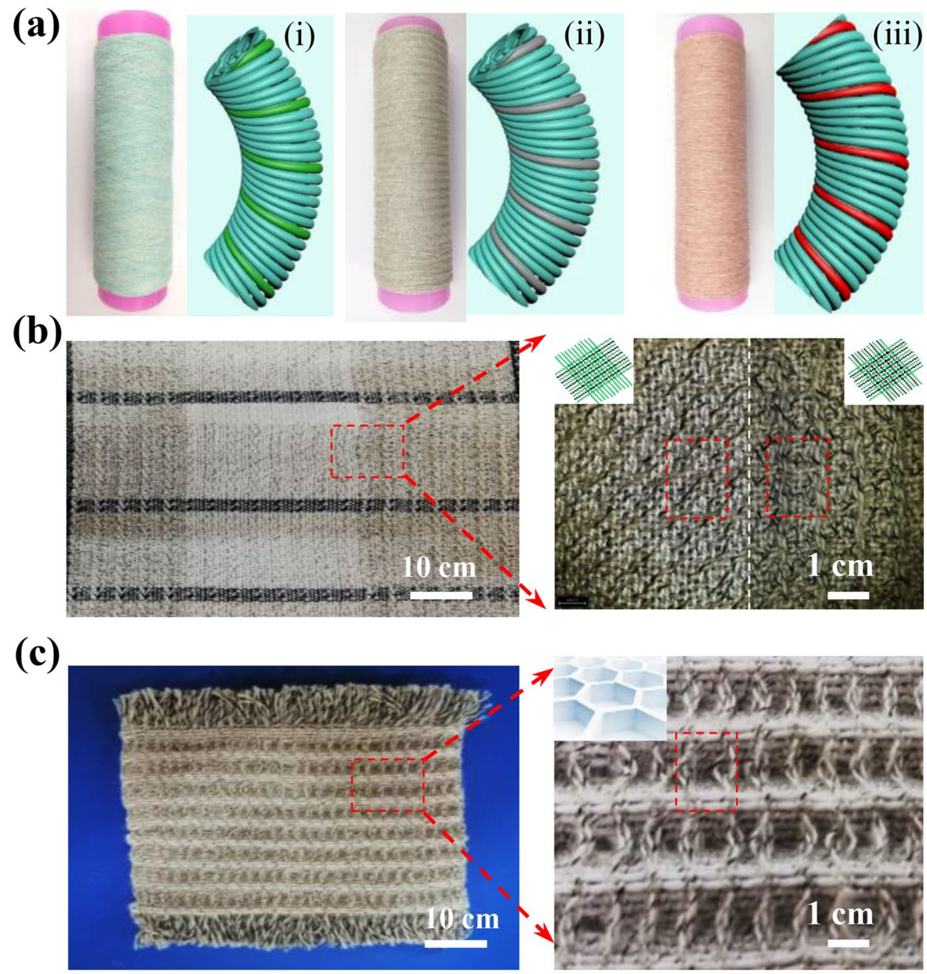

Fig. 5 **a** Composite yarns prepared from varied colored polyester filaments. Optical images of the woven textiles designed with **b** different patterns and **c** stereo visual effects

increased as a function of blend ratios, achieving a maximum mechanical strength of 1200 cN at the blend ratio of 1:8. These results could be assigned to the higher content of natural cotton staple fibers and strong interfacial interactions were formed between the two components. However, when the blend ratio was lower to 1:4, a relatively weak cohesive force would be formed between the two components and result in a loose/thinner shell cotton layer and lower linear density as compared to the predesigned (e.g. please see the samples obtained at the ratios of 1:2 and 1:3). On the contrary, as the blend ratio increased, the higher cotton content will possibly lead to a thicker shell layer and tight wrapping structure in the composite yarns. However, it needed to note that the extremely lower draft ratio in the PC8 sample will cause an incomplete drafting process and accompany with increased hairiness and unevenness value (Fig. 4c, d). In summary, the extremely higher blend ratio would lead to a higher yarn strength while processing poor hairiness and evenness performance, and in which conditions are not beneficial for the yarn weaving production. Thus, taking these aspects into consideration, a proper blend ratio of 1:4 has been employed to prepare the composite yarns with suitable mechanical strength of 686 cN, yarn density of 45 Tex., hairiness of 8.02 and unevenness of 8.84% that are beneficial for weaving.

Weaving performance and fabric texture

Finally, we demonstrated this spinning method was versatile that can be used to obtain various kinds colorful composite yarns and endow the weaved fabric with different patterns. To verify the versatility, as showed in Fig. 5a, another three different kinds of polyester filaments with distinct colors: (i) green, (ii) light gray and (iii) red have been tested. The optical images coupled with corresponding schematic diagrams indicated that various colorful yarns could be achieved by changing the filaments, and which spurred a promising physical spinning idea for the color spinning industry. Figure 5b, c are the optical observations of the textiles prepared from the segmented yarns (e.g. PC4). Particularly, Fig. 5b shows a new twill weaved fabric in a cycle unit (from left to right): the warp arrangement is composed of 168 interval colored yarns and 120 white cotton yarns while the weft arrangement is composed of 40 interval colored yarns and 12 black cotton yarns. The final textile showed an interweaving of interval color yarns, black and white cotton yarns, leading to different patterns in the fabric. For Fig. 5c, the warp yarns in the honeycomb fabric are all spaced color yarns, the weft yarns are white cotton yarns, and the number of weaving cycles is 10. It can be seen that the segmented yarns with interval color are interwoven and arranged with white yarns, resulting in a light gray and white colors on the cloth surface. Additionally, the black color segments are randomly distributed, which confers the fabric texture with the stereo visual effect. Importantly, it can be seen that the segmented color yarn can play a significant role for color harmony in the fabric, forming rich color changes and achieving the desired visualization.

Conclusion

In conclusion, the broad concept of colored spun yarn with a physical spinning method has been presented in this study. By controlling the inner and outer transfer movement of the black polyester filament and the natural cotton fiber, a novel kind of polyester/cotton composite yarn with the segmented structure and interval color sense has been successfully developed. Experimental results demonstrated that the blend ratio played a significant role for the composite yarn formation, achieving a better yarn performance at the ratio of 1:4. As indicated by the color systematic analysis, the alternating structural change would induce a unique interval color sense and gradient at the merged regions, resulting in an enhanced stereoscopic visual effect of the composite yarns as compared to the sirofil yarn made on a conventional ring frame. More importantly, three more kinds of colored polyester filaments have also been tested, revealing the fabricated composite yarns have an excellent versatility and weavability that can be designed with various fabric texture and visual senses. Therefore, by coupling the facile spinning method and multifunctionality of the composite yarns, we believe this work will facilitate a significant development of colored spun yarns for the fashion textile.

Supplementary information

Supplementary information accompanies this paper at https://doi.org/10.1186/s40691-020-00238-1.

Additional file 1: Video 1. Real-time monitoring of the spinning process before improvement.

Additional file 2: Video 2. Real-time monitoring of the spinning process after improvement.

Additional file 3. Electronic supplementary information containing of Figs. S1–S4.

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Authors' contributions
WW: Conceptualization, Writing-Reviewing and Editing, Funding acquisition; QT: Resources, Data curation and Modification; HT: Data curation; JC: Visualization; KY: Writing-Reviewing and Editing; DW: Conceptualization, Supervision. All authors read and approved the final manuscript.

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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. Residual amounts of materials tested in this project are stored on-site, and can be made using instructions provided in "Methods" section.

Competing interests
The authors declare no conflict interest.

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