A relative hairiness index for evaluating the securities of fiber ends in staple yarns and its application

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Abstract

Hairiness is a prominent property of staple yarns, but the existing evaluation parameters mainly describe the fiber ends already protruding out of yarn bodies. The potential fiber ends in yarns also play a crucial role in the performance of yarns in the subsequent processes and the resultant fabric quality. In our previous studies, maximum hairiness and its theoretical model have been proposed, which indicate the maximum fiber ends of a staple yarn having the potential to protrude out of yarn bodies and become hairy. On this basis, the relative hairiness index (RHI) is developed in this study to evaluate the fiber end tucking and securities of yarns. This index is treated as a ratio of the measured hairiness of sample yarns and the maximum hairiness of ring yarns in the same twist level and yarn count. A lower RHI indicates more fiber ends being tucked into yarn bodies, and a slower increment of the RHI with the increasing winding times represents more stable securities of fiber ends in yarns. The experimental results demonstrate that the RHI can directly reveal the effectiveness of different spinning parameters and methods in tucking and securing fiber ends; also, the changes of the RHI with increasing winding times visually present the stableness of fiber ends in various yarns experiencing abrasion, as well as predict the possibility of the potential fiber ends being pulled out to form hairiness during successive

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processes. The proposed RHI, therefore, provides a significant reference for the spinning process design and yarn quality control.

Keywords

Relative hairiness index, fiber securities, staple yarns, low-twist spinning

Introduction

Spinning, for staple fibers, is a process of tucking or securing fiber ends together to form a successive fiber assembly, namely yarn. Hairiness is a crucial parameter evaluating the status of protruding fiber ends, loops and wild fiber out of yarn bodies, and is one of the important yarn surface characteristics.[1,2] Since the 1950s, several methods[3-8] and instruments[9-18] have been developed to characterize yarn hairiness, notably the Uster Tester, Uster Zweigle hairiness tester, SDL hairiness tester, Lawson Hemphill tester, Keisokki Laserspot tester, amongst others; in addition, the most novel solutions for yarn hairiness measurement were mainly based on digital image processing and signal processing.[19,20] Notwithstanding this, only two methods were universally accepted and commercially utilized in textile industries and institutions: (a) an array of sensors measures the length of fiber ends protruding out of the yarn core; and (b) the amount of light scattered by the protruding fibers is used to calculate a hairiness index value for the yarn. There is a general belief that short fiber ends protruding out of yarn bodies give rise to a pleasant tactile sensation of resultant fabrics; whereas fiber ends over 2 mm may bring about disturbance in the successive processes and affect the surface characteristic and performance of final fabrics.[21] Therefore, hair length should be included when describing the hairiness of yarns. The well-known Uster Zweigle hairiness tester working on the principle of sensor arrays for hairiness testing can provide the number of yarn hairs with certain distances from the yarn core (1 mm, 2 mm, 3 mm, and so on), as well as the S3 value indicating the total number of hairs with the length of 3 mm and longer.[11,15] Also, the latest Uster testing device working on the principle of light scattering for yarn hairiness measurement, that is Uster Tester 6 with Sensor HL, can provide the number of hairs with seven different lengths (1, 2, 3, 4, 6, 8 and 10 mm), as well as S3u and S1+2u. In particular, S3u indicates the sum of hairs which are 3 mm and longer (cumulative); and S1+2u represents the sum of hairs with the length of 1 mm and 2 mm (cumulative).[14]Additionally, the hair density distribution profile was proposed by several researchers to evaluate yarn hairs, which was achieved by means of a charge-coupled device camera system.[21] Nevertheless, all the above parameters only describe the existing hairiness on yarn surface. Recently, maximum hairiness and its statistical model were proposed,[22] which is the theoretical number of fiber ends in ring staple yarns having the potential to protrude out of yarn bodies after spinning, and these fiber ends may be pulled out to become hairs when yarns endure abrasion with their adjacent yarns or machine parts in subsequent processing, such as winding, warping, weaving or knitting. Abundant potential fiber ends in yarns will result in difficulties in the successive processes and an unfavorable fabric surface. Thus, it is highly necessary to develop a hairiness index to evaluate the quantities or degree of potential fiber ends tucked or secured in yarns. On the basis of maximum hairiness, this paper proposes a relative hairiness index (RHI). The RHI of yarns spun with various spinning parameters and spinning methods, as well as their indications on fiber end tuck- ing and securities, will be systematically analyzed in this study.

Definition of RHI

In our previous study[22], the fiber ends with a certain length in the surface layer of a unit length of ring-spun yarn was reckoned to have the potential to protrude out of yarn bodies to become hairs, so the number of these fiber ends are defined as the maximum hairiness, which can be calculated from equation (1) and (2)[22],

$$\xi\left(N_{H\geq L_e}\right) = h_0 \sum_{i=1}^{m} \frac{2n_i}{\bar{L}\cos\beta_i}(\Delta - L_e \cos\beta_i)[1 - F(L_e)] \tag{1}$$

$$h_0 = \frac{\pi d N_y \delta \left(2\sqrt{\dfrac{\sqrt{1+\tan^2\overline{\beta}}}{\pi N_y \delta}} - d \right)}{\sqrt{1+\tan^2\overline{\beta}}} \tag{2}$$

where $N_{H\geq L_e}$ is the number of protruding fiber ends (namely hairiness) with and above the length of L_e per unit yarn length; L_e is the length of fiber ends (mm); h_0 is hairiness contribution factor; m is the total number of fiber layers in a yarn cross section; n_i is the number of fibers in the ith shell; $\bar{L}$ is the mean fiber length; β_i is the twist angle of the fibers in the ith layer; Δ is the unit yarn length, and here it is regarded as 1cm; $F(L_e)$ is the accumulative distribution density of fiber length L_e; d is fiber diameter (mm); N_y is the yarn count in Nm system; δ is the yarn density (g/cm^3); and $\bar{\beta}$ is the mean twist angle of the fibers in a yarn cross-section.

The above maximum hairiness model, established on the basis of an ideal open-packing compact yarn structure of ring yarns,[22] can be deemed as the maximum limit of hairs for staple yarns. Analogous to the theoretical limit of yarn evenness CV_{lim},[23] the real yarn hairiness could be approaching but is always lower than the limit value, namely the maximum hairiness. The gap between the theoretical maximum hairiness and the measured yarn hairiness may be narrowed or enlarged by varied spinning methods, different spinning parameters, subsequent processing, and other influences. Treating the maximum hairiness of ring-spun yarns as the baseline, the RHI for the hairs with the length of L_e and above gives

$$RHI_{\geq L_e} = \frac{\overline{N}^{t}_{H\geq L_e}}{\overline{N}_{H\geq L_e}} \tag{3}$$

where, $\overline{N}^{t}_{H\geq L_e}$ is the mean of the tested number of hairs with the length of L_e or longer per 1cm of yarns; and $\overline{N}_{H\geq L_e}$ is the maximum hairiness of ring yarns with the length of L_e or longer per 1cm of yarns, which can be obtained from equation (1) and (2); in particular, $\overline{N}^{t}_{H\geq L_e}$ and $\overline{N}_{H\geq L_e}$ are in the same level of twist multiplier and yarn count.

Equation (3) demonstrates that the lower the RHI is, the less the protruding fiber ends are on yarn surface, and the more potential fiber ends are left in yarn surface layers which may be pulled out of yarn bodies to become hairiness when yarns experienced abrasion. Additionally, the effectiveness of various spinning methods in tucking fiber ends into yarn bodies could be revealed by comparison with the RHI of their yarns. The maximum of *RHI* is 1.00, which means that the measured number of hairs is equal to the theoretical maximum value, that is, all the fiber ends in the yarn surface layer protrude out of yarn bodies. This is nearly impossible, because there must be some fiber ends being steadily secured in yarns by adjacent fibers after spinning process. The minimum of the RHI is zero, which is when no fiber ends in the yarn surface layer are pulled out of yarn body, and this can be represented by filament yarns.

Materials and methods

In this section, material specifications for yarn spinning, experimental design and characterization of yarn hairiness, as well as calculation of the RHI, are introduced.

Materials

The re-combed and shrink-resist treated wool roving was utilized for preparing multiples of staple yarns (AgResearch Ltd.), the specifications of which are presented in Table 1. The physical and mechanical prop-erties of wool fibers are influenced by their moisture regain and temperature,[24] which relate to the ambient temperature and relative humidity. In order to influence the performance of wool fibers during yarn formation, as well as the properties of resultant yarns, all roving were conditioned before spinning for about 24 h at the standard environment of 20±2℃ and 65±2% relative humidity.

Table 1 Wool roving specifications

Properties	Values
Roving count (Nm)	1.38 (2 ends)
Roving evenness (CVm%)	5.03
Fiber hauteur length (mm)	72.0 (CVH: 42.0%)
Fiber diameter (microns)	18.8 (CVD: 21.8%)
Fibers over 30 microns (%)	1.3

Note: the measured fiber hauteur length was regarded as mean fiber length for the calculation of the relative hairiness index.

Experimental design

From equation (1)-(3),the influencing factors of the RHI include yarn twist, yarn count, yarn density, fiber length, fiber diameter and the measured yarn hairiness. Particularly, the RHI variance of each yarn sample resulting from the measured yarn hairiness could be avoided by using a fixed testing device and carefully following the testing standard; yarn density (in grams per cubic centimeter) is not an adjustable parameter during spinning, but it relates to yarn twist and spinning methods, amongst others.[25] To simplify the complexity, the fiber material remained unchanged in this study, the specifications of which are exhibited in Table 1. Then, yarn twist, yarn count and spinning methods were the main influencing factors of the RHI. Thus, the effectiveness of the three factors in fiber tucking and securities will be systematically researched by means of the proposed RHI in this study, which could provide a guidance in designing spinning process and yarn quality control.

As presented in Table 2, seven levels of twist multipliers and four kinds of yarn counts were adopted in this study, respectively. In addition, various ring-based spinning systems were chosen to investigate their differences in the effectiveness of fiber tucking and securities: conventional ring spinning, Siro-spinning, Solo-spin- ning and low-twist spinning. In particular, low-twist spinning is also named as low torque or Nu-torque™ spinning, which is a modified ring spinning technology developed by Tao et al.' s team.[26,27] To exclude the influence of yarn count on yarn hairs, all samples in the part were spun with the same yarn count of 36 Nm (i.e. 27.8 tex). To ensure the most suitable twist multiplier for each kind of yarn, ring and Siro-spun yarns were prepared with the twist multiplier adopted most in spinning factories; however, the twist multipliers of low-twist yarns and Solo-spun yarn were set based on the optimization results in our previous study.[28] Consequently, as shown in Table 2, for knitting yarns, 36 Nm low-twist yarns with the twist multiplier of 72 and Solo-spun yarn with the twist multiplier of 85 were spun and compared with conventional ring knitting yarns with the twist multiplier of 85; for weaving yarns, 36 Nm low-twist yarns with the twist multiplier of 115 by feeding a double-end roving, Siro-spun yarns with the twist multiplier of 135 and Solo-spun yarns with the twist multiplier of 120 were spun and compared with conventional ring weaving yarns with the twist multiplier of 90. Additionally, the gaps of two single roving in both the Siro-spun system and the Low-twist+Siro-spun system were 14 mm, which is a generally optimized width.

All yarn samples were prepared on the wool spinning machine Zinser 451 in the laboratory of the Hong Kong Polytechnic University. All the cop yarns were spun at the same spindle speed of 7800 rpm and sampled on three fixed spindles for each kind of yarn, which were positioned at the left side, the middle side and the right side of the spinning area, respectively, to avoid machining errors. Then, all cop yarn samples were wound at a speed of 300 m/min on a Savio winding machine. The tension of winding was set at the lowest level to avoid high end-breakage of some weaker yarns. "Cop" and "Cone" are short for yarn samples before and after winding, respectively. Furthermore, the hairiness of staple yarns tended to flatten out after four-time winding,[22,29] thus the hairiness after the fourth winding was named as stable hairiness; accordingly, the yarn samples with stable hairiness are coded as "Stable".

Table 2 General experimental design

Factors \ Spinning parameters		Yarn count (Nm)	(tex)	Twist multiplier (α_m)	Spinning methods	Traveler (Kanai ISO No.)	Roving gap (mm)	Yarn code
Twist multiplier		36	27.8	75	Conventional Ring	8.9	N.A.	36CONV-75
		36	27.8	85	Conventional Ring	8.9	N.A.	36CONV-85
		36	27.8	95	Conventional Ring	8.9	N.A.	36CONV-95
		36	27.8	105	Conventional Ring	8.9	N.A.	36CONV-105
		36	27.8	115	Conventional Ring	8.9	N.A.	36CONV-115
		36	27.8	125	Conventional Ring	8.9	N.A.	36CONV-125
		36	27.8	135	Conventional Ring	8.9	N.A.	36CONV-135
Yarn count		24	41.7	120	Conventional Ring	12.3	N.A.	24CONV-120
		28	35.7	120	Conventional Ring	10.9	N.A.	28CONV-120
		32	31.3	120	Conventional Ring	10.4	N.A.	32CONV-120
		36	27.8	120	Conventional Ring	8.9	N.A.	36CONV-120
Spinning method	Knitting yarns	36	27.8	85	Conventional Ring	8.9	N.A.	36CONV-85K
		36	27.8	85	Solo	8.9	N.A.	36Solo-85K
		36	27.8	72	Low twist	10.9	N.A.	36LT-72K
	Weaving yarns	36	27.8	90	Conventional ring	8.9	N.A.	36CONV-90W
		36	27.8	135	Siro	8.9	14	36Siro-135W
		36	27.8	120	Solo	8.9		36Solo-120W
		36	27.8	115	Low twist+Siro	10.9	14	36LT+Siro-115W

Note: Nm is an indirect unit of metric yarn count, which is the length per 1g of yarn; tex is a direct unit of yarn count, which is the mass per 1000m of yarn; α_m is the twist multiplier in metric count; Kanai is the brand of traveler, and ISO No. indicates traveler weight in millligrams; Low-twist+Siro represents the low-twist spinning system with double-end roving feeding, and the gap of the two roving was 14mm. NA: not applicable.

Measurement of yarn hairiness

Zweigle G566 was used to examine yarn hairiness in this study. Yarns of 100 m length were measured for each test. Three tests were continuously performed for each yarn sample according to the standard ASTM D1423, and three samples of each kind of yarn were selected randomly for hairiness testing. In addition, the testing speed was set as 100 m/min according to Wang's report about the effect of testing speed on yarn hairiness for the Zweigle hairiness tester.[30] S3, which is the number of yarn hairs with the length of 3 mm and above, can be directly obtained. The numbers of hairs in 12 length groups (1 mm, 2 mm, 3 mm, and so on), were achieved. All yarn samples were conditioned for over seven days at a standard atmosphere of 20±2℃ and 65±2% relative humidity before examination. All the examinations were performed in the same standard atmosphere.

Calculation of RHI

The total number of the detected yarn hairs $\overline{N}_{H\geq 1mm}^{t}$ and $\overline{N}_{H\geq 3mm}^{t}$ for each kind of yarn were accordingly calculated based on the measured hairiness values. The corresponding theoretical maximum hairiness including $\overline{N}_{H\geq 1mm}$ and $\overline{N}_{H\geq 3mm}$ can be calculated from equations (1) and (2). Then, the $RHI_{\geq 1mm}$ and $RHI_{\geq 3mm}$ of each type of yarn can be obtained from equation (3).

Results and discussion

RHI of yarns with different twist multipliers

As presented in Table 3, the *p*-values from the one-way analysis of variance (ANOVA) of four groups of worsted yarns in seven twist levels are all less than the significance level of 0.01, which reveal that the differences of the RHIs in different twist levels are significant at the confidence interval of 99%. This result is similar to the relationship of yarn twist and measured hairiness data.[31] By means of Pearson correlation analysis, the correlation of twist multiplier and RHI is significant at the 1% level as shown in Table 4, which further implies that the RHI closely relates to the yarn twist multiplier. However, equation (3) uses the measured hairiness data and the theoretical hairiness data in the same twist level when calculating the RHI; thus, in theory, the twist multiplier should not have a significant correlation with the RHI. The contradiction between the theoretical interference and the practical results could be explained by the different influencing degrees of the twist multiplier on the theoretical maximum hairiness and the measured yarn hairiness. With the increasing yarn twist, our previous research showed that the maximum hairiness was slightly enhanced, but the measured hairiness gradually decreased.[22] It can be inferred that the measured hairiness reduced more quickly than the maximum hairiness increased with the increasing twist multiplier, leading to the reduction of the RHI when yarn twist enhanced as presented in Table 3 and Figure 1.

Table 3 *RHI* of worsted yarns with different twist multipliers

Yarn code	$RHI_{>=1mm}$		$RHI_{>=3mm}$	
	Cop	Cone	Cop	Cone
36CONV-75				
Mean	0.24564	0.37142	0.04094	0.07837
CV%	[0.830]	[1.738]	[0.264]	[0.391]
36CONV-85				
Mean	0.23011	0.35052	0.03857	0.07434
CV%	[0.920]	[1.146]	[0.284]	[0.364]
36CONV-95				
Mean	0.21356	0.34823	0.03469	0.07482
CV%	[0.724]	[1.968]	[0.197]	[0.320]
36CONV-105				
Mean	0.19760	0.30498	0.03397	0.06585
CV%	[0.844]	[0.875]	[0.110]	[0.171]
36CONV-115	0.20942	0.28843	0.03456	0.06082
Mean				
CV%	[0.800]	[0.969]	[0.107]	[0.190]
36CONV-125	0.20223	0.27982	0.03253	0.05217
Mean				
CV%	[1.116]	[0.792]	[0.223]	[0.610]
36CONV-135	0.19564	0.25059	0.03160	0.05165
Mean				
CV%	[1.297]	[1.135]	[0.235]	[0.198]
P value (ANOVA test)	0.0001	0.0000	0.0011	0.0000

Note：Yarn count=36Nm, significance level=0.01.

RHI: relative hairiness index

Table 4 Correlation of RHI and twist multiplier

		$RHI_{>=1mm}$ (cop)	$RHI_{>=1mm}$ (cone)	$RHI_{>=3mm}$ (cop)	$RHI_{>=3mm}$ (cone)
Twist multiplier	Pearson Correlation	-0.882*	-0.984*	-0.932*	-0.974*
	Sig. (2-tailed)	**0.009**	**0.000**	**0.002**	**0.000**

*. Correlation is significant at the 0.01 level (2-tailed).

Figure 1 shows that the RHI of 36 Nm worsted yarns gradually decreased with the increasing twist multiplier from 75 to 135; in particular, both the $RHI_{\geqq 1mm}$ and $RHI_{\geqq 3mm}$ of cop yarns reduced by over 20%, and those of cone yarns approximately dropped by 33%, that is, more fiber ends in both the cop yarns and cone yarns with higher twist multipliers were tucked into yarn bodies than those of the yarns with lower twist multipliers. It is demonstrated that raising the yarn twist is conducive to tucking fiber ends into yarn bodies. In addition, the $RHI_{\geqq 1mm}$ and $RHI_{\geqq 3mm}$ of cone yarns are both higher than those of cop yarns, which illustrates that some potential fiber ends are not stably secured in worsted yarn bodies after spinning, thus they are liable to being pulled out of the yarn surface to become new hairiness when the yarns experience abrasion during winding. This is consistent with the finding in our previous study.[22] The differences between the RHI of the cop yarns and the cone yarns with the same yarn count and twist multiplier were slowly narrowed by 56.3% for $RHI_{\geqq 1mm}$ and 58.2% for $RHI_{\geqq 3mm}$ with the twist multiplier increasing from 75 to 135, respectively, as presented in Figure 1, which further proved that more fiber ends having the potential to become hairs could be stably secured in yarn bodies by adding yarn twist level. This has not been revealed in the previous studies.

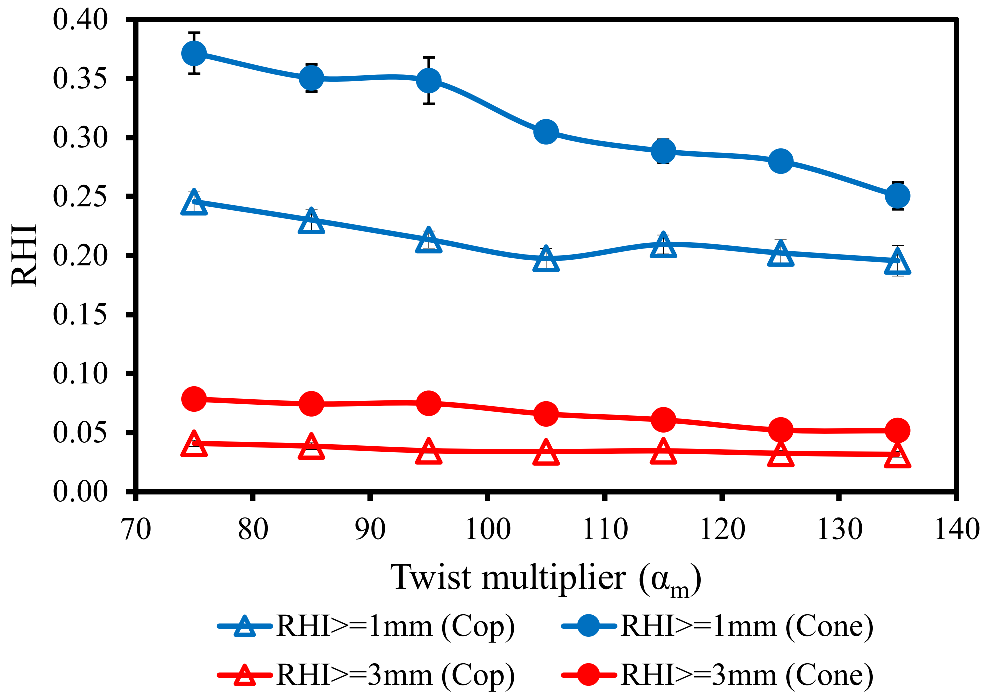


Figure 1 *RHI* of 36Nm worsted yarns with the increasing twist multiplier

RHI of yarns with different yarn counts

To verify the effect of yarn count on the RHI, the RHI of worsted yarns in four kinds of yarn counts, 24 Nm (41.7 tex), 28 Nm (35.7 tex), 32 Nm (31.25 tex) and 36 Nm (27.8 tex), but with the same twist multiplier of 120, are presented in Table 5. The results show that the *p*-values of $RHI_{\geqq 1mm}$ and $RHI_{\geqq 3mm}$, both for cop and cone yarns, were less than the significance level of 0.05, which means that there are significant differences of the RHI among the yarns with different yarn counts at the confidence interval of 95%; and all the RHI presented a mild decrease with the increasing metric yarn count as depicted in Figure 2, which agrees with Barella and Manich's experimental results of cotton ring yarns.[32] Nonetheless, for the confidence interval of 99%, the *p*-value (i.e. 0.0159) of the $RHI_{\geqq 3mm}$ for the cop yarns with four kinds of yarn counts is higher than the significant level of 0.01, that is, the four $RHI_{\geqq 3mm}$ values have significant differences, whereas the other three RHI indicators (i.e. $RHI_{\geqq 1mm}$ of cop yarns and cone yarns, $RHI_{\geqq 3mm}$ of cone yarns) varies significantly when the yarn count changes.

Further more, the Tukey honestly significant difference (HSD) post hoc test was determined to verify the specific differences of the RHI in each two groups of yarn counts at the confidence interval of 95%. As shown in Table 6, some *p*-values higher than the significance level of 0.05 are randomly distributed among the comparison results of RHI in each two groups of yarn counts, which implies that there are no significant differences of the RHI of the two yarns. Therefore, yarn count seems to have a slight correlation with the RHI of yarns, which could be explained by equation (3), in which the RHI is calculated from the measured hairiness and the theoretical maximum hairiness in the same yarn count, and unlike the twist multiplier, the degree of the influence of yarn count on the measured hairiness may not markedly differentiate from that on the theoretical maximum hairiness. Thus, the RHI does not seem to closely correlate with yarn count. It is worth noting that this finding is different from Wang's research on yarn hairiness, which revealed that yarn count was reckoned as the third important factor on yarn hairiness among spinning parameters excluding fiber material specifications.[33]

Table 5 *RHI* of worsted yarns in different yarn counts

Yarn code		$RHI_{>=1mm}$		$RHI_{>=3mm}$	
		Cop	Cone	Cop	Cone
24CONV-120	mean	0.25957	0.35851	0.04705	0.07492
	CV%	[0.788]	[0.690]	[0.123]	[0.298]
28CONV-120	mean	0.24575	0.35254	0.04689	0.07391
	CV%	[0.774]	[1.122]	[0.120]	[0.169]
32CONV-120	mean	0.24493	0.34924	0.04543	0.07339
	CV%	[0.903]	[0.880]	[0.109]	[0.121]
36CONV-120	mean	0.23354	0.32905	0.04512	0.07106
	CV%	[0.584]	[0.884]	[0.216]	[0.207]
P value* (ANOVA test)		0.0000	0.0000	0.0155	0.0036
P value** (ANOVA test)		0.0000	0.0000	**0.0159**	0.0036

Note： αm=120, * significance level=0.05, ** significance level=0.01. ANOVA: analysis of variance; RHI: relative hairiness index.

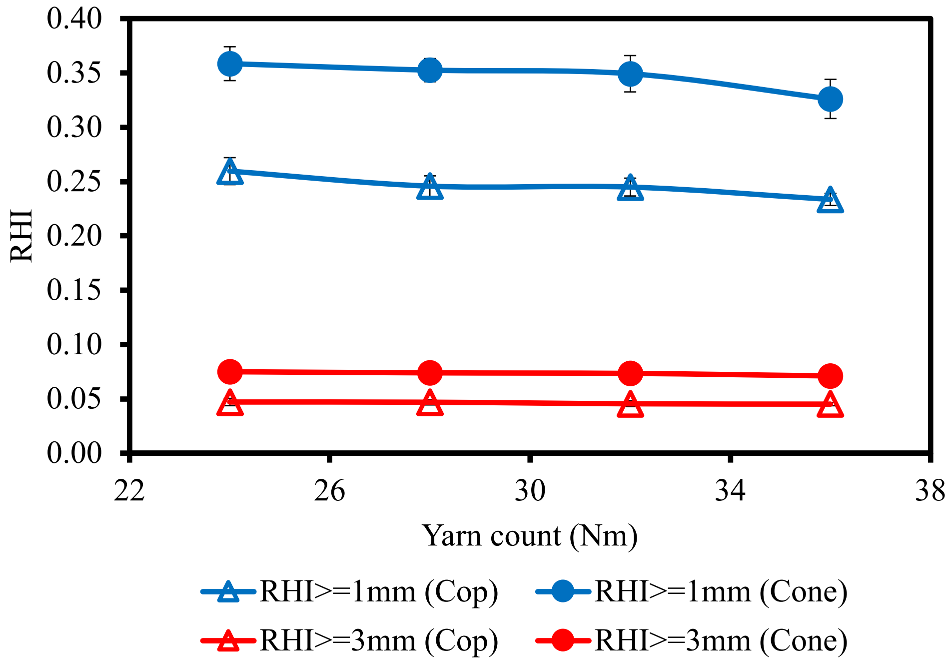


Figure 2 *RHI* of worsted yarns in different yarn counts (α_m=120)

Table 6 Tukey HSD post-hoc test results for *RHI* of worsted yarns in different yarn counts

Yarn code (Nm)	P values			
	$RHI_{>=1mm}$ Cop	$RHI_{>=1mm}$ Cone	$RHI_{>=3mm}$ Cop	$RHI_{>=3mm}$ Cone
24CONV-120 vs 28CONV-120	0.002	**0.193**	**0.784**	**0.390**
24CONV-120 vs 32CONV-120	0.002	0.024	0.009	**0.182**
24CONV-120 vs 36CONV-120	0.000	0.000	0.033	0.006
28CONV-120 vs 32CONV-120	**0.839**	**0.497**	0.016	**0.464**
28CONV-120 vs 36CONV-120	0.002	0.000	**0.052**	0.006
32CONV-120 vs 36CONV-120	0.006	0.000	**0.708**	0.010

Note：α_m=120, significance level=0.05

RHI of different types of yarns

In this section, the RHI of several types of 36 Nm knitting yarns and weaving yarns in three situations were examined, respectively. The three situations are cop yarns, cone yarns and stable yarns, which separately represent the spun yarns enduring zero-time, one-time and four-time winding or abrasion. The changes of the RHI of each kind of yarn at three situations could evaluate the stableness of fiber security in yarns when yarns endure abrasion. Usually, the RHI increases when the yarn transforms from cop yarn to stable yarn, that is, the RHI increases with the advanced winding or abrasion times. For the three forms of yarns, the faster the RHI grows when the yarn form changes from cop to cone, then to stable, the worse the fiber ends are secured in the yarn body.

RHI of knitting yarns spun with different spinning methods

Table 7 shows the $RHI_{\geq 1mm}$ and $RHI_{\geq 3mm}$ of three kinds of 36 Nm knitting yarns: ring yarns (coded as 36CONV-85K), Solo-spun yarns (coded as 36Solo-85K) and low-twist yarns (coded as 36LT-72K). The *p*-values of all RHIs of the three types of yarns are lower than the significance level of 0.01 by ANOVA test and Tukey HSD post hoc test, that is, the RHI is significantly differentiated by yarn type (Table 8). This indicates that spinning methods could affect the fiber end tucking in these knitting yarns.

Table7 *RHI* of knitting yarns spun with different spinning methods

Yarn code		$RHI_{>=1mm}$			$RHI_{>=3mm}$		
		Cop	Cone	Stable	Cop	Cone	Satble
36CONV-85K	mean	0.24309	0.36968	0.44764	0.04231	0.07636	0.10703
	CV%	[0.810]	[0.580]	[2.010]	[0.170]	[0.226]	[0.289]
36Solo-85K	mean	0.21337	0.28531	0.29931	0.03743	0.05554	0.06166
	CV%	[0.794]	[0.362]	[1.140]	[0.184]	[0.211]	[0.152]
36LT-72K	mean	0.30833	0.41611	0.56917	0.05042	0.10351	0.16065
	CV%	[0.376]	[0.766]	[0.683]	[0.187]	[0.179]	[0.347]
P value (ANOVA test)		0.0000	0.0000	0.0011	0.0000	0.0000	0.0000

Note：yarn count=36Nm, significance level=0.01. ANOVA: analysis of variance; RHI: relative hairiness index.

Table 8. Tukey honestly significant difference post hoc test results for relative hairiness index of knitting yarns spun with different spinning methods

Yarn code	p-values					
	$RHI_{>=1mm}$ Cop	$RHI_{>=1mm}$ Cone	$RHI_{>=1mm}$ Stable	$RHI_{>=3mm}$ Cop	$RHI_{>=3mm}$ Cone	$RHI_{>=3mm}$ Stable
36CONV-85K vs	0.000	0.000	0.000	0.000	0.000	0.000

36Solo-85K						
36CONV-85K Vs 36LT-72K	0.000	0.000	0.000	0.000	0.000	0.000
36Solo-85K vs 36LT-72K	0.000	0.000	0.000	0.000	0.000	0.000

Note: yarn count = 36 Nm, significance level = 0.01. RHI: relative hairiness index.

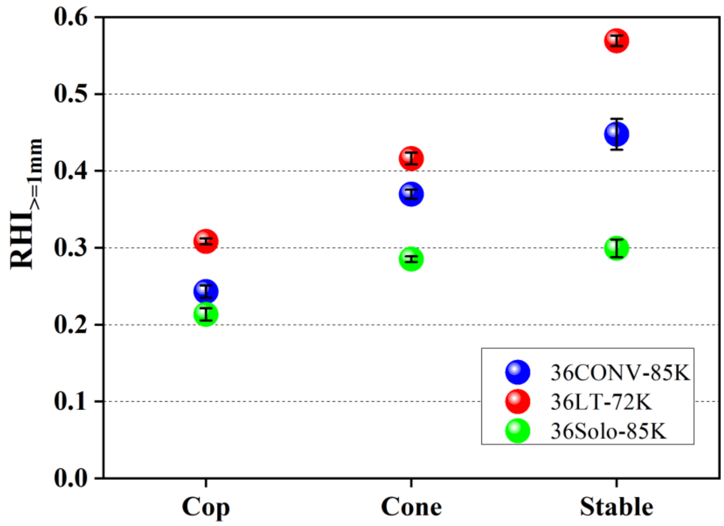
Table 9 Tukey HSD post-hoc test results for *RHI* of knitting yarns spun with different spinning methods

Yarn code	P values					
	$RHI_{>=1mm}$ (Cop)	$RHI_{>=1mm}$ (Cone)	$RHI_{>=1mm}$ (Stable)	$RHI_{>=3mm}$ Cop	$RHI_{>=3mm}$ Cone	$RHI_{>=3mm}$ Satble
36CONV-85K vs 36Solo-85K	0.000	0.000	0.000	0.000	0.000	0.000
36CONV-85K vs 36LT-72K	0.000	0.000	0.000	0.000	0.000	0.000
36Solo-85K vs 36LT-72K	0.000	0.000	0.000	0.000	0.000	0.000

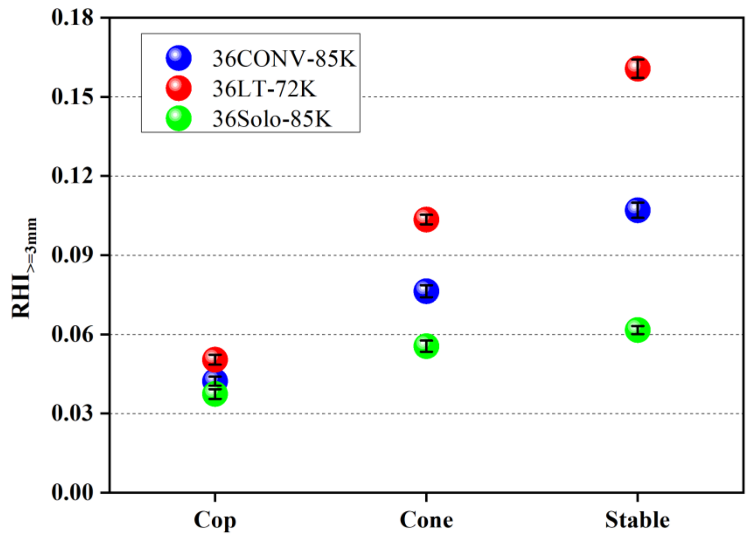
Note：yarn count=36Nm, significance level=0.01. ANOVA: analysis of variance; RHI: relative hairiness index.

As shown in Figure 3, the $RHI_{\geqq 1mm}$ and $RHI_{\geqq 3mm}$ of 36LT-72K were generally higher than that of 36CONV-85K and 36Solo-85K in all three situations; and the RHI of 36Solo-85K had the lowest values.The differences of the $RHI_{\geqq 1mm}$ and $RHI_{\geqq 3mm}$ among three kinds of yarns increased with the increasing winding times. The increment rates of the $RHI_{\geqq 1mm}$ of 36LT-72K and 36CONV-85K were higher than that of 36Solo-85K, and the $RHI_{\geqq 3mm}$ of 36LT-72K advanced fastest among the three types of knitting yarns, which was followed by that of 36CONV-85K. This result reveals that low-twist knitting yarns possess lower fiber security, even lower than conventional ring yarns. There may be two reasons: firstly, the high resilience and rigidity of wool fibers[25] bring about the difficulties in holding wool fiber deformation in yarns produced by the false-twisting in a low-twist spinning system; secondly, the shrunken spinning triangle resulting from the effect of the false-twisting[34] does not facilitate the ends of long staple wool fibers to be wrapped into yarns. Interestingly, compared with conventional ring yarns, the improvement of the low-twist spinning modification on the wool fiber migration in yarn bodies could be demonstrated to some extent by means of the RHI of yarns, which avoids the tedious experiments of traditional fiber migration examination.

On the contrary, the $RHI_{\geqq 1mm}$ and $RHI_{\geqq 3mm}$ of 36Solo-85K not only presented the lowest values among the three kinds of knitting yarns, but also they climbed the slowest with the increasing winding times, and even the RHI of Solo-spun stable yarns seemed similar to that of stable yarns. It is demonstrated that Solo-spinning can effectively and stably tuck and secure fiber ends into yarn bodies, which may be attributed to the several tiny substrands divided by the Solo-spun roller in the spinning triangle. The intermittently changing substrands and their interaction enhanced the fiber migration in Solo-spun yarns.[35,36]



(a) $RHI_{\geq 1mm}$



(b) $RHI_{\geq 3mm}$

Figure 3 *RHI* of knitting yarns spun with different spinning methods

RHI of weaving yarns spun with different spinning methods

Table 9 shows the $RHI_{\geq 1mm}$ and $RHI_{\geq 3mm}$ of four kinds of 36 Nm weaving yarns: conventional ring yarns (coded as 36CONV-90W), Siro-spun yarns (coded as 36Siro-135W), Solo-spun yarns (coded as 36Solo-120W) and low-twist yarns (coded as 36LT+Siro-115W). Most RHIs of the four types of weaving yarns exhibited significant differences by ANOVA test (as shown in Table 9) and Tukey HSD post hoc test (as shown in Table 10) at the significant interval of 99% , except for the $RHI_{\geqq 1mm}$ of 36Siro-135W and 36LT+Siro-115W cop yarns. The p-value of the two $RHI_{\geqq 1mm}$ was 0.251, which is higher than the significance level of 0.01. It is demonstrated that the $RHI_{\geqq 1mm}$ of the two kinds of yarns did not vary significantly. It is indicated that low-twist spinning with double-end roving feeding has a similar effect on tucking fiber ends into yarn bodies to Siro-spinning. However, the RHI of 36LT+Siro-115W advanced more quickly than that of 36Siro-135W with the increasing winding times as described in Figure 4, which demonstrates that the combination of low-twist spinning and Siro-spinning fails to secure fiber ends more stably than Siro-spinning. This may be caused by the shrunken spinning triangle resulting from the effect of false-twisting,[34] which contributes to fewer long protruding fiber ends being secured into yarn bodies in the low-twist spinning system than in the Siro-spinning system.

Additionally，Figure 4 shows that 36CONV-90W had the relatively highest $RHI_{\geqq 1mm}$ and $RHI_{\geqq 3mm}$ among four kinds of weaving yarns and increased fastest with the augmented winding times, followed by 36Solo-120W and 36LT+Siro-115W, and 36Siro-135W had the lowest values; in each situation, namely, cop, cone and stable, the RHI of 36LT+Siro-115W seemed similar to that of 36Solo-120W yarns. This observation reveals that: (a) ring spinning has the lowest effectiveness in tucking and securing fiber ends in yarn bodies; (b) low-twist spinning with double-end roving feeding could tuck and secure approximate fiber ends to Solo-spinning; and (c) Siro-spinning presents the highest effectiveness in tucking and securing fiber ends of weaving worsted yarns. The superiority of Siro-spun worsted yarns in securing fiber ends may contribute to its higher mean fiber position and higher migration factor as compared by Soltani and Johari.[37] In a word, Siro-spinning, Solo-spinning and low-twist spinning with double-end roving feeding can promote fiber ends being tucked in weaving yarn bodies and improve the stableness of fiber security of staple yarns, particularly Siro-spinning. In addition, like Solo-spun knitting yarns, there were nearly no apparent increments of $RHI_{\geqq 1mm}$ and $RHI_{\geqq 3mm}$ of the Solo-spun weaving yarns after four-time winding by comparison with those of cone yarns, which illustrates that Solo-spun yarns possess good fiber security both for knitting yarns and weaving yarns. This is attributed to the high fiber migration resulting from the intermittently changing substrands and their interaction of Solo- spinning.[35,36]

Last but not least, compared with the RHI of low-twist knitting yarns (coded as 36LT-72K) and low-twist weaving yarns (36LT+Siro-115W) in three situations (i.e. cop, cone and stable), the $RHI_{\geqq 1mm}$ and $RHI_{\geqq 3mm}$ of 36LT+Siro-115W were apparently lower than those of 36LT-72K, the reasons for which lie in two parts: firstly, the double-end roving feeding facilitates tucking fiber ends in the spinning triangle and securing fiber ends into yarn bodies, as described in our previous study;[28,38] secondly, the higher twist level of low-twist weaving yarns (twist multiplier is 115) contributes to more fiber ends being tucked and secured in yarns than low-twist knitting yarns (twist multiplier is 72).

Table 10 *RHI* of weaving yarns spun with different spinning methods

Yarn code		$RHI_{>=1mm}$			$RHI_{>=3mm}$		
		Cop	Cone	Stable	Cop	Cone	Satble
36CONV-90W	mean	0.23620	0.34596	0.50902	0.03863	0.06844	0.13452
	CV%	[1.061]	[1.135]	[1.135]	[0.156]	[0.254]	[0.432]

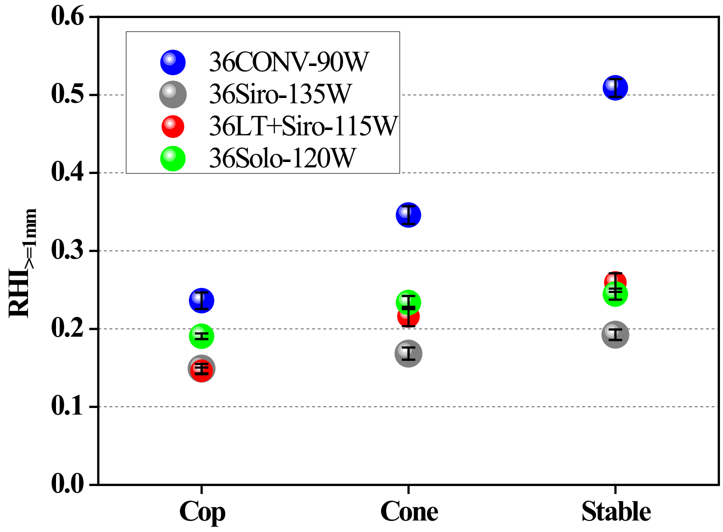
36Siro-135W	mean	0.14908	0.16835	0.19251	0.01726	0.02317	0.02982
	CV%	[0.599]	[0.788]	[0.672]	[0.095]	[0.085]	[0.084]
36Solo-120W	mean	0.19058	0.23381	0.24452	0.02792	0.04384	0.04662
	CV%	[0.366]	[0.842]	[0.709]	[0.079]	[0.127]	[0.196]
36LT+Siro-115W	mean	0.14618	0.21587	0.25938	0.01924	0.03775	0.05138
	CV%	[0.418]	[1.230]	[1.198]	[0.148]	[0.243]	[0.493]
P value (ANOVA test)		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Note：yarn count=36Nm, significance level=0.01

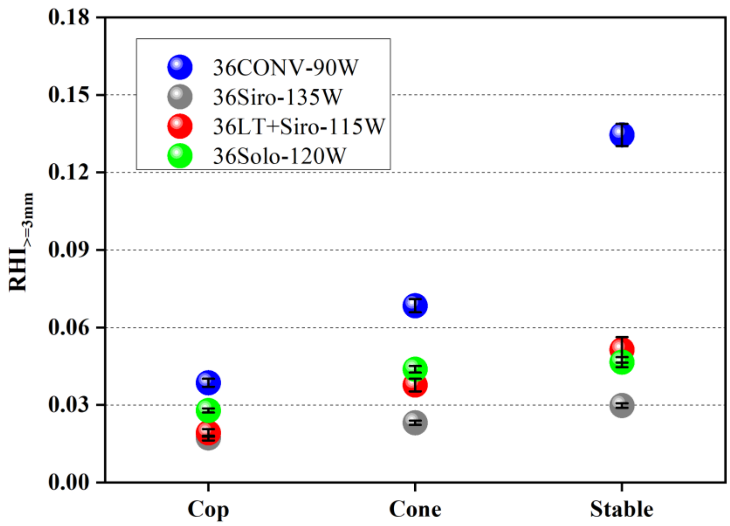
Table 11 Tukey HSD post-hoc test results for *RHI* of weaving yarns spun with different spinning methods

Yarn code	P values					
	$RHI_{>=1mm}$ (Cop)	$RHI_{>=1mm}$ (Cone)	$RHI_{>=1mm}$ (Stable)	$RHI_{>=3mm}$ (Cop)	$RHI_{>=3mm}$ (Cone)	$RHI_{>=3mm}$ (Satble)
36CONV-90W vs 36Siro-135W	0.000	0.000	0.000	0.000	0.000	0.000
36CONV-90W vs 36Solo-120W	0.000	0.000	0.000	0.000	0.000	0.000
36CONV-90W vs 36LT+Siro-115W	0.000	0.000	0.000	0.000	0.000	0.000
36Siro-135W vs 36Solo-120W	0.000	0.000	0.000	0.000	0.000	0.000
36Siro-135W vs 36LT+Siro-115W	**0.251**	0.000	0.000	0.003	0.000	0.000
36Solo-120W vs 36LT+Siro-115W	0.000	0.002	0.000	0.000	0.000	0.002

Note：yarn count=36Nm, significance level=0.01



(a) $RHI_{>1mm}$



(b) $RHI_{>3mm}$

Figure 4 *RHI* of weaving yarns spun with different spinning methods

Conclusions

The commonly used yarn hairiness parameters, such as S3 from Uster Zweigle hairiness tester and S3u from Uster Tester 6, only evaluated the hairs already existing on the yarn surface, but failed to provide the information about the fibers having the potential to become hairy when the yarn endured abrasion in the subsequent processes, which also played a crucial role in yarn and fabric qualities. The RHI proposed in this research, which combined the measured existing hairiness value and the theoretical maximum fiber ends having the potential to protrude out of yarn bodies, not only could reveal the hairiness status of yarns, but also could exhibit the stableness of fiber securities in yarns, that is, the possibilities of hairiness increment during yarn experiencing abrasion. Compared with the RHI of conventional worsted ring yarns with different yarn twists and yarn counts, a higher twist level facilitated tucking and securing fiber ends into yarn bodies and reducing the possibilities of potential fiber ends being pulled out of yarns to become new hairs; however, yarn count did not seem to have a significant effect on the RHI of yarns, which is different from the previous findings about the relationship of yarn count and measured yarn hairiness. In addition, it is unexpected that the RHI of low-twist knitting yarns were higher and advanced faster with the increasing winding times than ring and Siro-spun yarns, which revealed that the modification of false-twisting on the ring spinning system failed to secure wool fibers stably in yarns; on the other hand, the better performance of the RHI of Low-twist+Siro-spun yarns demonstrated that a higher twist and double-end roving feeding significantly improved the securities of fiber ends in low-twist yarns. In the future, more related studies will be carried out to improve the index comprehensively, describing the potential fiber ends in varied yarn structures and their tendency to form real hairs.

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