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Investigation of the effect of denim washing on surface characteristics and deformation behavior using a novel instrument

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ABSTRACT

In the current study, the surface characteristics and deformation behavior of raw and washed denim fabrics were investigated using Tactile Sensation Analyzer (TSA) which measures surface variations through sound analysis and determines out-of-plane deformation behavior during the deformation test phase. A total of 30 denim fabrics with various raw materials and production parameters were examined. Two different denim washing processes were applied to the raw denim fabrics, one involving cellulase enzyme and the other combined with pumice stones. The effects of washing on structural properties, surface characteristics, deformation, elasticity, hysteresis, plasticity, and tactile comfort were analyzed. The results indicated that denim washing significantly increased the thickness and decreased the magnitude of micro-surface variations across all tested samples, and most fabrics exhibited a less rigid structure after washing. It was detected that enzyme washing has a moderate effect on fabric properties. Meanwhile, the combination of cellulase enzyme and pumice stones resulted in significant improvements in surface smoothness, fullness, unit mass, deformability, elasticity and total hand scores.

Keywords
denim washing,
surface characteristics,
deformation behavior,
comfort,
Tactile Sensation Analyzer

1 Introduction

Denim fabric is a warp-faced twill-weave fabric commonly produced with indigo dyed cotton warp yarns and undyed weft yarns. Indigo dye can be washed out from the garment's surface by applying several washing methods which provide the unique worn-out look of denim. In addition to the changes in visual aspects created by washing treatments, these processes may alter the surface profile and low-stress mechanical properties such as bending rigidity, extensibility and shear rigidity. Several researchers studied the effect of washing treatments on color and structure [1], mechanical properties [2,3,4] and moisture management characteristics [5] of denim fabrics. Nevertheless, the effect of washing on sensory properties [6,7] and tactile comfort [8,9] was rarely investigated.

Tactile comfort is directly related to the interactions between skin and fabric and is determined by the structural, mechanical and surface properties of fabrics [10,11]. It is expected that any denim washing process which decreases the rigidity and surface roughness may provide an improved tactile comfort. It was previously reported that the application of stone washing and the combination of the stone wash with bleaching created desirable hand evaluation results [7]. Stone washing was detected to be the most effective method to improve tactile comfort and low-stress mechanical properties of denim fabrics [8]. It was also presented that enzyme-washed fabrics have a better hand and lower hardness properties; stone-washed fabrics have a higher fluffy feel, bleach-washed fabrics have a worse hand, and rinse-washed fabrics have stiffer and rougher surfaces [9].

Tactile comfort of textiles is determined by surface characteristics, rigidity, and a combination of several other properties which usually include low-stress mechanical properties such as extensibility, shear behavior etc. [12,13]. Several low-stress mechanical properties of conventional woven fabrics such as bending rigidity and extensibility can easily be measured using conventional test methods and equipment [14]. On the other hand, because of their complicated nature, it is relatively difficult to objectively measure fabric properties such as pure-shear behavior [15] or surface smoothness-roughness [11,16,17].

There are several test methods suggested for determining surface characteristics of textiles [18,19,20]. Measurement systems such as Kawabata Evaluation System (KES-F) [21,22], Fabric Assurance by Simple Testing (FAST) [23,24], Comprehensive Handle Evaluation System for Yarns and Fabrics (CHES-FY) [25], and Fabric Touch Tester (FTT) [26] were developed by researchers to evaluate the hand of fabrics by a series of objective measurements. In addition to these measurement systems, several researchers proposed single measurement devices which evaluate fabric hand within a single testing process, where a circular fabric sample is pushed or pulled through a ring, or a nozzle and the resistance of the fabric sample is recorded [27,28,29]. Fabric extraction technique can provide valuable information regarding drape and tactile characteristics of fabrics [22,24,30]. However, the load-displacement graph must be carefully interpreted [31,32] and in some cases the raw data may need to be normalized [33].

Tactile Sensation Analyzer (TSA) is a novel instrument designed to measure surface and low-stress mechanical properties of textile structures [33,34]. The device uses a unique sound analysis technique to measure the magnitude of micro and macro-surface variations [35], meanwhile the deformation and recovery characteristics in out-of-plane deformation state were determined by deformation tests [36].

Conventional measurement systems consist of a number of separate test modules where the components of fabric hand are measured independently and fabrics were tested in each direction (warp, weft, diagonal etc.). On the contrary, TSA has a single test unit which implements all necessary measurements in succession and determines surface and deformation characteristics in a circular test area, using a single sample for all measurements [37,38]. The test unit of TSA is connected to a computer where the results are immediately displayed by the software, which is a time and labor-saving option. Unlike common test equipment which was primarily designed for evaluating tactile comfort of conventional woven fabrics, TSA is compatible with various textile structures including nonwovens, woven fabrics, knitted fabrics and terry towels [33,35,39].

In the current study, surface characteristics and low-stress mechanical properties of denim fabrics were investigated before and after washing. A total number of 30 denim fabrics made of 100% cotton or blends of cotton with linen, polyester, and lyocell was studied. The fabrics were washed using pumice stones and cellulase enzyme. Surface characteristics, deformation and recovery behavior of raw and washed denim fabrics were measured using TSA. Tactile comfort of fabrics was determined by sensory evaluations. The effect of denim washing on structural, surface, mechanical and tactile properties was presented. The relation between fabric properties and tactile comfort was also discussed based on statistical measures.

2 Method

2.1 Material

For the study, 10 raw denim fabrics were procured from a local denim mill (Table 1). Most of the investigated denim fabrics were made of 100% cotton warp and weft yarns, one sample (CLY) was made of cotton/lyocell (60/40) blend yarns, one sample (CP) was made of cotton/polyester (82/18) blend weft yarns, and one sample (CLI) was made of 100% linen weft yarns. Three of the 100% cotton denim fabrics were indigo coated (IN1, IN2 and DIN). The procured raw denim fabrics were categorized as set R.

2.2 Denim washing

In industrial applications, denim washing is usually applied to the sewn garment and mainly the face side of the fabric is subjected to washing. To better imitate the industrial conditions, raw denim fabrics were cut as 1 m^2 samples, folded in half and sewn along one edge to form a shape similar to the denim end-products such as shirts, skirts or trousers, and fabrics were placed to the washing machine face side out.

Raw denim fabrics were washed according to two recipes prescribed in Table 2. One of the washing processes was carried out with cellulase enzyme and named enzyme washing (EW). The other washing process was carried out using both cellulase enzyme and pumice stones, and it was named as stone washing (SW). All other steps of the washing processes were identical (Table 2). In the last stage of washing, a regular finishing with a micro silicone softener was applied.

Table 1. Production parameters of raw denim fabrics.

Fabric code	**Weave pattern**	**Warp yarns**	**Weft yarns**	**Warp count** *(Tex)*	**Weft count** *(Tex)*	**Warp setting** *(cm^{-1})*	**Weft setting** *(cm^{-1})*	**Mass per unit area** *(g/m^2)*
IN1*	2/1 Twill	Cotton	Cotton	26	25	45	27	201
IN2*	2/1 Twill	Cotton	Cotton	26	25	45	26	212
DIN**	2/1 Twill	Cotton	Cotton	30	30	39	22	202
C1	2/1 Twill	Cotton	Cotton	37	27	35	22	202
C2	3/1 Twill	Cotton	Cotton	20	20	50	34	190
C3	2/1 Twill	Cotton	Cotton	27	25	44	26	199
C4	3/1 Twill	Cotton	Cotton	20	23	53	29	195
CLI	Plain	Cotton	Linen	20	42	32	21	189
CLY	2/1 Twill	Cotton 60% Lyocell 40%	Cotton 60% Lyocell 40%	30	30	40	23	207
CP	3/1 Twill	Cotton	Cotton 82% Polyester 18%	30	30	36	24	197

*Indigo coated denim fabric, **Double indigo coated denim fabric

Table 2. Stages of denim washing processes.

	Pre-washing	**Rinsing**	**Denim washing***		**Rinsing**	**Softening**	**Drying**
			EW	**SW**			
Duration	5 min	3 min	10 min	10 min	3 min x2	5 min	45 min
Temperature	40 °C		40 °C	40 °C		40 °C	70 °C
Material			Enzyme[c]	Enzyme[c] Stone[p]		Softener[m]	

*EW: enzyme washing, SW: stone washing.
[c] Cellulase enzyme (2 g/L), [p] Pumice stone (ratio 1/12, size 2-4), [m] Micro silicon (5 g/L).

2.3 Measurements

Surface characteristics (micro-surface variations and macro-surface variations), low-stress mechanical properties (deformation, elasticity, plasticity, and hysteresis) and structural properties (thickness and mass per unit area) of fabrics were determined by objective measurements. The conditioning and testing of samples were carried out at standard atmospheric conditions, as specified in EN ISO 139.

3 Test

3.1 Structural properties

Mass per unit area of fabrics was determined according to EN 12127:1997. Fabric thickness under 5 gf/cm^2 pressure was measured using James Heal R&B Cloth Thickness Tester, having a circular presser foot with 100 mm^2 size. Mass per unit area and thickness measurements were carried out as five replicates.

3.2 Tactile Sensation Analyzer

Tactile Sensation Analyzer (TSA) is designed by the German company Emtec Electronic GmbH to measure hand related properties of various textile structures [34]. In the current study, TSA was used to measure surface variations and deformation characteristics (Fig. 1). For TSA measurements, five samples were prepared for each fabric type. The sample dimensions were 120 mm x 120 mm and the face side of each specimen was subjected to the measurements.

3.3 Surface characteristics

For the measurement of micro-surface variations (TS7) and macro-surface variations (TS750), the sample is fixed to the circular frame and the zero position of the measuring head is calibrated when the blades contact with the sample surface with a load of 100 mN. To determine surface characteristics, the blades of the measuring head rotate on the fabric's surface (Fig. 1a). The vibrations provide information about the surface structure of the fabric. The sound caused by these vibrations is recorded by two microphones, placed above and below the test sample and using the sound spectrum, macro-surface variations and micro-surface variations were determined.

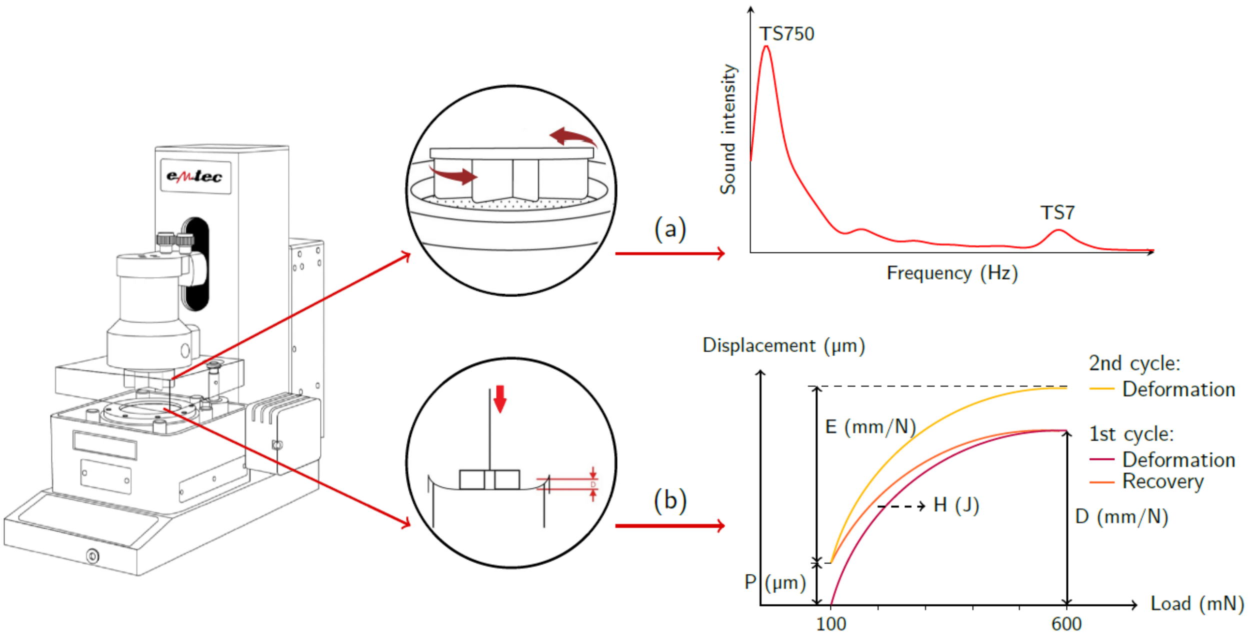

Fig. 1 Tactile Sensation Analyzer and graphical representation of (a) rotation of the blades, sound spectrum, micro-surface variation peak (TS7) and macro-surface variation peak (TS750); (b) out-of-plane deformation (D), hysteresis (H), plasticity (P), and elasticity (E).

3.4 Low-stress mechanical properties

Several deformation parameters can be measured by TSA in out-of-plane deformation and recovery stages. Deformation measurement has three successive steps [36]. In the beginning of the first cycle, the blades of measuring head contact with the test sample with a load of 100 mN. Then the measuring head moves further down until a 600 mN load is reached. In this stage the magnitude of out-of-plane deformation (D) is measured (Fig. 1b). The second step is the recovery step. In this step, the measuring head moves up and the magnitude of permanent deformation (plasticity, P) and the energy generated during recovery (hysteresis, H) are determined. In the current study absolute values of P were used. In the third step, the measuring head moves downwards until a 600 mN load is reached for the second time. The out-of-plane deformation recorded in this step is recorded as elasticity (E).

3.5 Sensory evaluation of tactile comfort

Total Hand (TH) scores of investigated denim fabrics were evaluated via sensory tests. It was previously reported that it is possible to obtain reliable results even with a sensory panel of 5 to 10 assessors [40]. It was also suggested that including female assessors with a higher level of expertise can significantly increase the accuracy of the findings. With respect to the previously reported statistical findings, in the current study, sensory evaluations were carried out by participation of 6 expert female assessors.

For tactile comfort evaluations, one sample was prepared for each fabric type (70 mm x 70 mm) and a total number of 30 denim samples were presented to the assessors in a random positioning and order. During the assessments, panel members were asked to rank the samples using a five-point scale: poor (1), fair (2), average (3), good (4) and excellent (5) tactile comfort. The evaluation process was unconstrained, and no time limit was enforced. As the participants were expert assessors who are familiar with sensory evaluations, no trial session was carried out. The evaluations were realized as a single trial, no repetition trial was conducted.

3.6 Statistical analysis

The distribution of the data was not fitting the standard normal distribution; therefore, the significance of relations and differences were investigated using non-parametric statistical methods.

The effect of washing processes on fabrics' surface structure, mechanical properties and total hand score was evaluated using mean values of replicate measurements. The results of raw and washed denim fabrics of the same kind were paired and the significance of the differences between paired data sets was investigated using Wilcoxon Signed Rank Test. The significant differences at 95% confidence level (2-tailed) were reported.

Correlation between total hand scores and mechanical, structural and surface properties of fabrics was determined by calculating Spearman's rank-order correlation coefficients. The significant correlation relations were reported for 90%, 95% and 99% confidence levels (2-tailed).

4 Results

In the current study, it was observed that washing noticeably increased the total hand (TH) scores of all investigated denim fabrics (Fig. 2) and the differences between raw and washed denim pairs were statistically significant for both enzyme washing (EW) and stone washing (SW) ($p = 0.005$). The effect of EW on improving fabric hand was on a moderate level (between 0.2 and 1 points on a 5-point scale). EW was especially effective on improving the hand of samples CLI and CP (1 point). Meanwhile, EW showed the minimum effect on indigo coated samples (IN1, IN2 and DIN) (≤ 0.5 points).

It was previously stated that stone washing was a more effective technique than enzyme washing in terms of improving tactile comfort [8]. In accordance with the previous literature, SW provided a more prominent improvement in tactile comfort when compared to EW (between 0.8 and 2.2 points). Unlike EW, the stone washing process was very effective on improving hand of indigo coated samples (≥ 1.5 points).

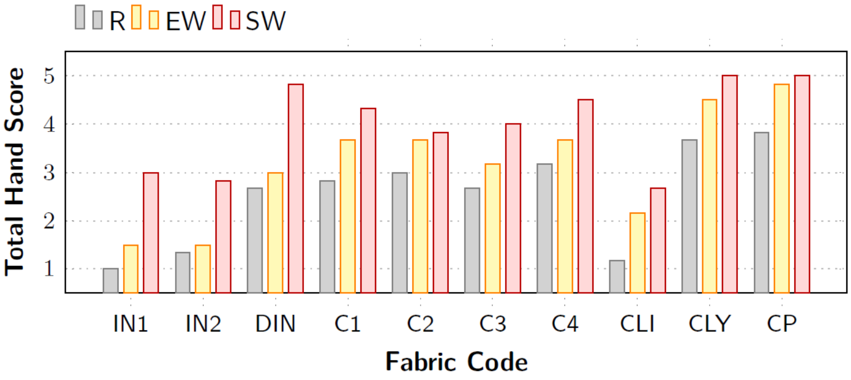

Fig. 2 Total Hand Scores of raw (R), enzyme washed (EW) and stone washed (SW) denim fabrics

4.1 Effect of washing on structural properties

Mass per unit area of fabrics was not affected by EW ($p > 0.05$) (Fig. 3). On the other hand, SW caused a moderate increase in unit weight of denim fabrics which detected to be statistically significant ($p = 0.011$). The most noticeable change was 9.04% which was recorded for cotton/polyester blend sample (CP). No significant correlation relation was detected between mass per unit area and TH scores of denim fabrics ($p > 0.1$). Therefore, it was concluded that the unit mass of investigated denim fabrics does not have a major effect on overall fabric hand.

Both denim washing processes resulted in a significant increase in fabric thickness ($p = 0.005$) (Fig. 3). The increase obtained in thickness by EW was between 13% and 40%, and for SW it was between 19% and 52%. The thickness of cotton/polyester blend sample (CP) was the most affected and the cotton/linen blend sample (CLI) was the least. Statistical calculations proved that TH scores of investigated denim fabrics were significantly correlated and directly proportional to the thickness results ($r_s = 0.790$, $p = 0.000$). Based on these findings it was assumed that the apparent increase in the fullness of fabrics achieved through EW and SW may have contributed to the improvement in TH scores.

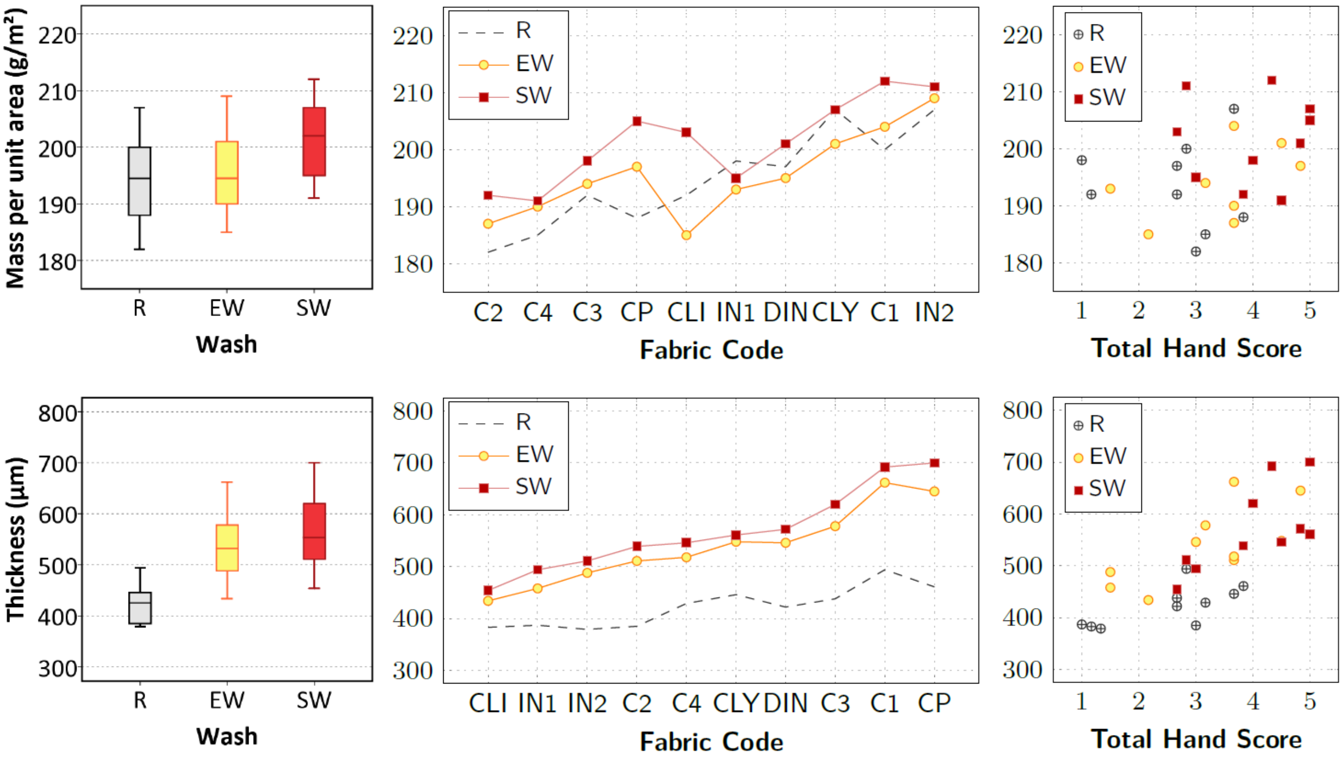

Fig. 3 Mass per unit area and thickness of raw (R), enzyme washed (EW) and stone washed (SW) denim fabrics and their relations with total hand scores.

4.2 Effect of washing on surface characteristics

Micro and macro-surface variations of face sides of fabrics were investigated using the sound analysis technique of TSA (Fig. 1a). As can be seen in Fig. 4, both washing processes created a noticeable decrease in micro-surface variations, and the differences between micro-surface variations of raw and washed denim pairs were statistically significant ($p = 0.005$). The indigo coated raw denim sample IN1 had the highest micro-surface variation result among all samples, which decreased by 44% and 64% after EW and SW, respectively. Besides, SW provided a noticeable decrease in micro-surface variations of IN2, CLI and CLY (≥ 40%). Effect of washing on micro-surface variations of the rest of the samples was on a similar level with an average decrease of 32%.

In comparison to micro-surface variations, the effect of washing on the macro-surface variations was less significant. As can be seen in Fig. 4, several denim fabrics exhibited noticeably lower macro-surface variations after washing. Meanwhile macro-surface variations of a number of samples remained within a similar range. Statistical investigations pointed a significant difference between macro-surface variations of raw and stone washed denim pairs ($p = 0.037$). On the other hand, no significant difference was detected between macro-surface variations of raw and EW denim pairs ($p > 0.05$).

Hand of textiles might be predominantly related to several fabric characteristics, therefore it is expected to observe significant relations between sensory evaluation results and laboratory tests. In the current study, TH score of denim fabrics was found to be significantly correlated with and inversely proportional to the magnitude of micro-surface variations ($r_s = -0.882$, $p = 0.000$). TH scores of fabrics were also inversely proportional to macro-surface variations ($r_s = -0.360$, $p = 0.051$), however, this correlation relation was less significant compared to micro-surface variations (Fig. 4).

In a previous study, surface structure of different types of fabrics was investigated using TSA and it was emphasized that - compared to macro-surface variations - the magnitude of micro-surface variations may be a more determinant attribute for comparing tactile comfort of conventional woven fabrics [33]. As TH scores of investigated denim fabrics were strongly dependent on the magnitude of micro-surface variations and moderately related to the magnitude of macro-surface variations, these findings were in accordance with the suggestions of previous literature.

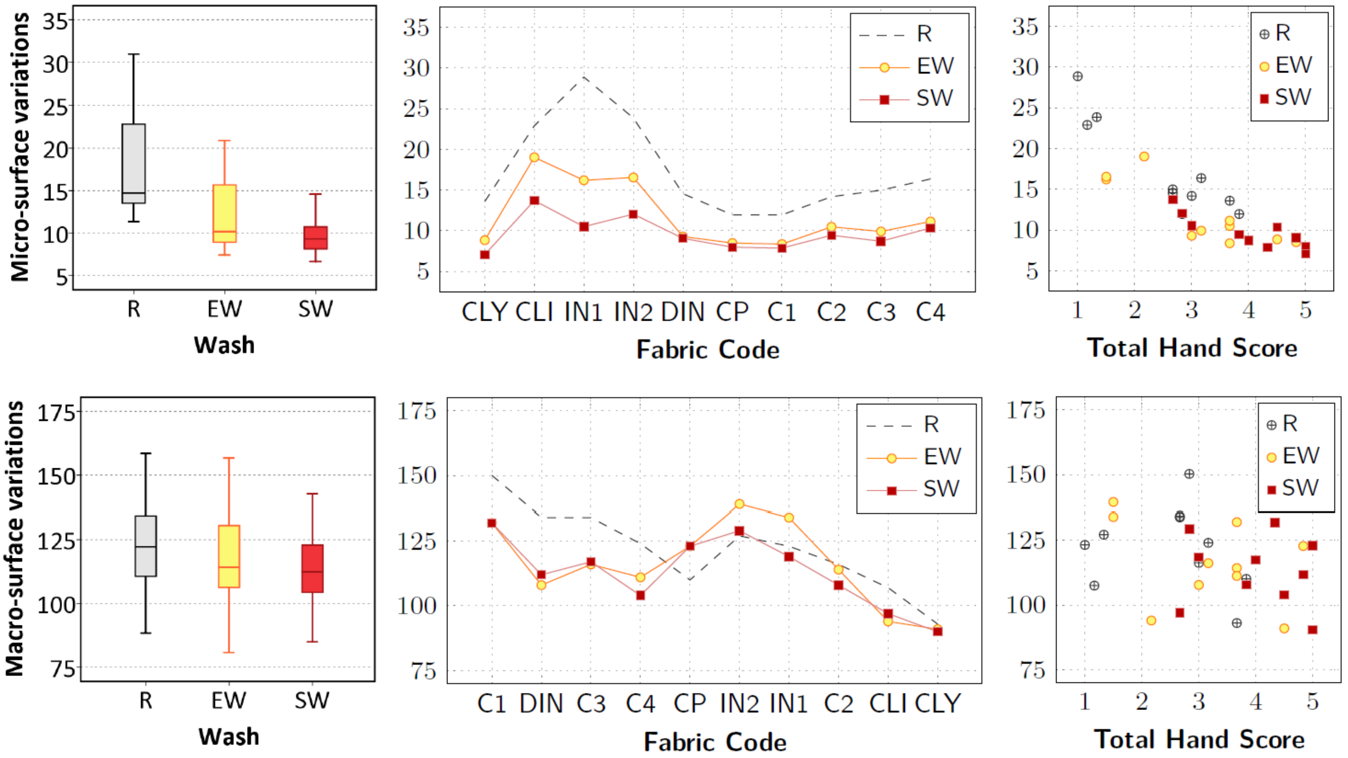

Fig. 4 Micro-surface variations and macro-surface variations of raw (R), enzyme washed (EW) and stone washed (SW) denim fabrics and their relations with total hand scores.

4.3 Effect of washing on deformation and elasticity

Deformation (D) and elasticity (E) of fabrics were measured using TSA during deformation test (Fig. 1b). Results indicated that denim sample made of linen weft yarns (CLI) and indigo coated samples - especially IN1 - have quite low deformation ability and elasticity (Fig. 5). On the contrary, the denim sample made of cotton/polyester blend (CP) exhibited the highest D and E values, which were further enhanced by EW and SW. In fact, in the current study almost all samples exhibited higher deformation results after washing. Statistical comparison of raw and washed denim pairs indicated that the increase in D values was significant for both EW and SW ($p = 0.025$ and $p = 0.011$, respectively). The samples with the most significant changes in D values were CP, CLI, IN1 and DIN (≥ 11%).

A similar improvement in elasticity (E) was also detected. It was observed that E of cotton/polyester blend sample (CP) and double indigo coated sample (DIN) was noticeably higher after SW (≥ 11%). Similarly, EW provided 15% and 12% increases in elasticity of CP and cotton/linen blend samples (CLI), respectively. Even though EW provided a noticeable increase in elasticity of several denim types, the difference between elasticity of raw and washed denim pairs was found out to be only significant for SW ($p = 0.021$), but not for EW ($p > 0.05$).

It was detected that tactile comfort of investigated denim fabrics was significantly correlated with and directly proportional to deformation and elasticity results ($r_s = 0.837$ and $r_s = 0.830$, respectively) ($p=0.000$). As deformation and elasticity results of studied denim fabrics were significantly improved after washing, the significant correlation relations proved that deformability under low-loads and elasticity are both desired qualities for a better fabric hand and these properties have a noticeable effect on tactile comfort of denim fabrics.

It was previously reported that deformation (D) and elasticity (E) parameters measured by TSA are a combination of woven fabrics' bending, shear and extension properties [36]. As parameters D and E are reported to be a combination of bending, shear and extension, findings of the current study were also in accordance with the previous literature in which it was reported that denim fabrics have a lower bending rigidity, lower shear rigidity, higher extension ability and a better tactile comfort after washing [8].

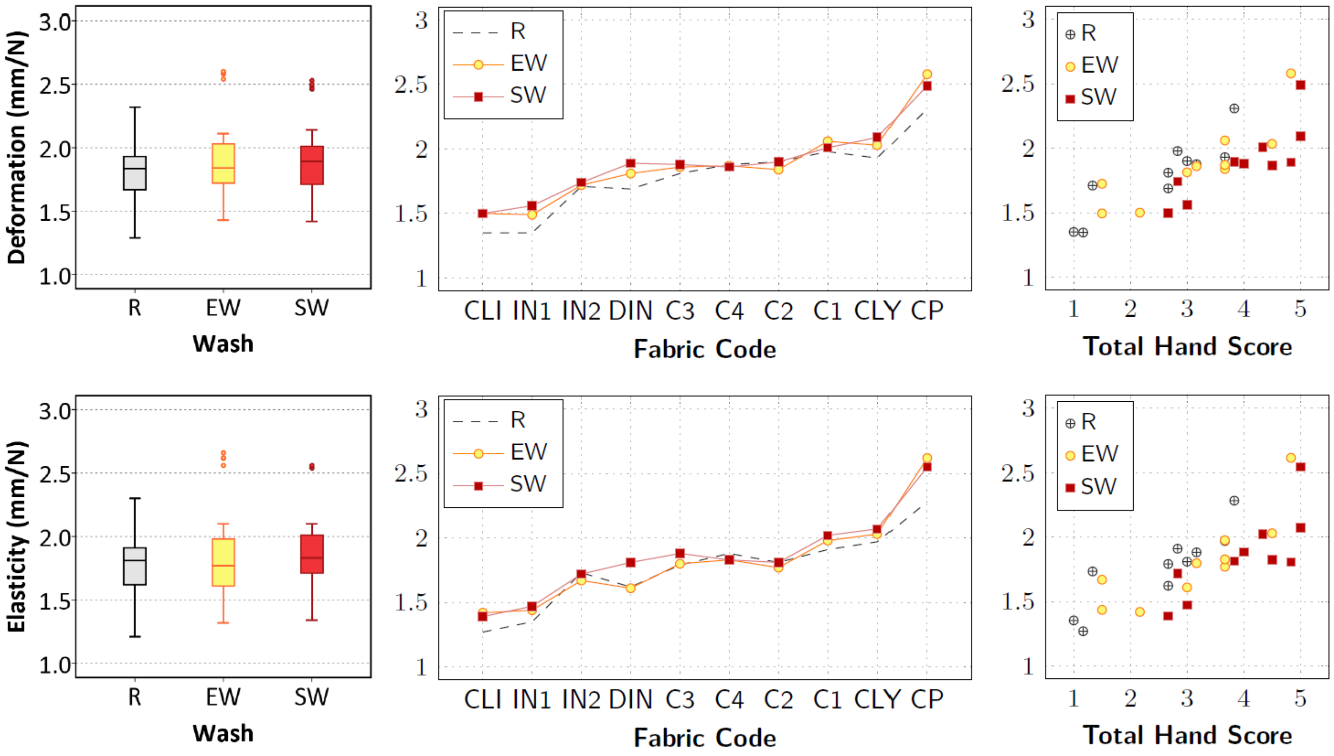

Fig. 5 Deformation (D) and elasticity (E) of raw (R), enzyme washed (EW) and stone washed (SW) denim fabrics and their relations with total hand scores.

4.4 Effect of washing on recovery characteristics

Plasticity (P) and hysteresis (H) of denim fabrics were measured using TSA during the recovery stage of deformation test (Fig. 1b). Plasticity (P) parameter measured by TSA refers to the magnitude of permanent deformation. In the current study, it was observed that 8 out of 10 fabrics exhibited higher plasticity results after enzyme washing (Fig. 6) and the difference between plasticity of raw and EW denim pairs was statistically significant (p = 0.037). The highest plasticity value across all fabrics was recorded for enzyme washed double indigo coated denim sample (DIN) which was increased by 104% after enzyme washing. EW created a prominent change in plasticity of samples IN1 and CLY as well (353% and 277%, respectively).

Even though the effect of SW on plasticity exhibited a similar trend, it was less prominent when compared to EW. The most noticeable effect of SW on plasticity was recorded for IN1 and CLY (427% and 320%, respectively), yet the difference between plasticity of raw and SW denim pairs in general was statistically not significant (p > 0.1).

Although the general effect of the washing process on plasticity was to increase this value, it was observed that washing may have an opposite effect on plasticity of some samples. For instance, plasticity of cotton/polyester blend sample (CP) was decreased by 20% and 36% after EW and SW, respectively. Similarly, plasticity of CLI was 24% lower after EW.

It was previously reported that tactile comfort of different types of fabrics may have different relations with plasticity [33]. For instance, plasticity of towels was associated with the compressibility of pile yarns, and it was reported that high plasticity is a desired quality for towels for a better tactile comfort. On the contrary, it was mentioned that bed sheets with higher P values were rated with lower TH scores, which might indicate that plasticity is a component that negatively affects the tactile comfort of conventional woven beds sheets. As can be seen in the irregular arrangement of the data in scatter plots (Fig. 6), no significant correlation between plasticity and TH scores was detected for investigated denim fabrics. Based on this observation it was concluded that plasticity may not necessarily determine the overall tactile comfort of investigated denim types.

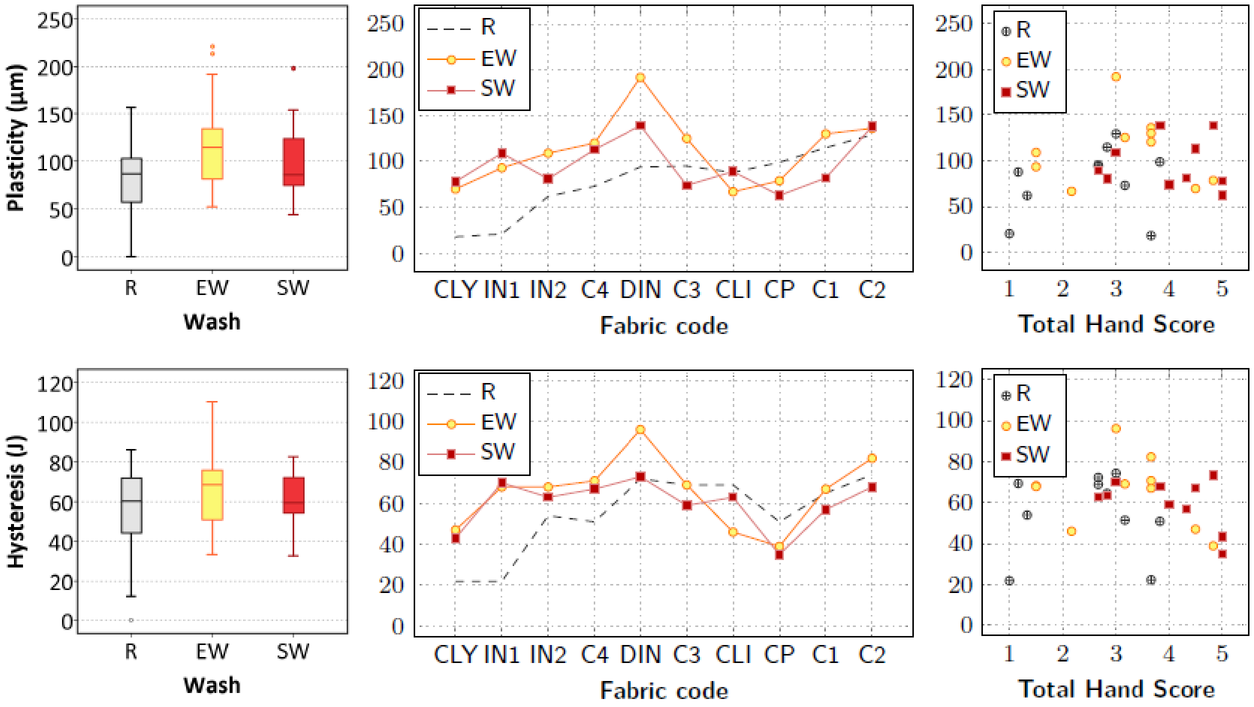

Fig. 6 Pasticity (P) and hysteresis (H) of raw (R), enzyme washed (EW) and stone washed (SW) denim fabrics and their relations with total hand scores.

The effect of enzyme washing on hysteresis was almost identical but slightly less prominent compared to plasticity (Fig. 6). The majority of the fabrics exhibited significantly higher hysteresis values after EW ($p = 0.093$). The highest hysteresis value was recorded for DIN after enzyme washing (96.1 J). EW and SW drastically increased hysteresis of IN1 (≥ 212%) and CLY (≥ 94%) as well. As an exception, SW and EW caused a decrease in hysteresis of some denim samples. Cotton/polyester blend sample (CP) exhibited lower hysteresis values after EW and SW (24% and 31%, respectively), and hysteresis of CLI was decreased by 34% after EW.

It was previously proved that hysteresis results of woven fabrics made of cotton and blends and used as bed sheets were inversely proportional to the tactile comfort, meanwhile no other significant correlation relation between hysteresis and tactile comfort was reported for other fabric types [36]. In the current study no significant correlation was detected between hysteresis and TH scores of denim fabrics ($p > 0.1$). These findings indicate that hysteresis property of textiles might have a minor importance on fabric hand compared to surface and deformation properties. As recovery characteristics (P and H) of investigated denim fabrics were not correlated with the TH scores of investigated denim types, it was concluded that the effect of denim washing on recovery properties may not be of high importance regarding the tactile comfort sensation of customers.

5 Conclusions

This study investigates the effect of enzyme and stone washing on surface, deformation, recovery and tactile properties of denim fabrics. The findings confirmed enzyme and stone washing processes significantly improved the overall tactile comfort sensation. Both washing processes were shown to enhance the fullness of the fabrics and the smoothness of the fabric surface. Sensory evaluation results of raw and washed denim fabrics were strongly and significantly correlated with thickness and micro-surface variations, indicating higher TH scores post-washing.

In addition to the improvements in structural and surface properties, it was observed that both washing processes led to noticeable enhancements in deformation (D) and elasticity (E) parameters. Statistical analyses demonstrated that TH scores of raw and washed denim fabrics were significantly correlated with and directly proportional to D and E values. Thus, the improvements in deformation and elasticity contributed to a marked increase in tactile comfort.

The study further highlighted that stone washing was particularly effective in enhancing surface structure, deformability and consequently the tactile comfort of denim fabrics, as compared to enzyme washing. Given that both enzyme and stone washing processes involve identical steps and chemical components, except for the inclusion of pumice stones in stone washing, it suggests that better tactile comfort can be achieved by incorporating pumice stones, without increasing the overall process conditions (e.g., duration, temperature) or the amount of treatment agents used.

Finally, as four out of six parameters measured by TSA were significantly correlated with the TH scores of denim fabrics, this study recommends the use of the device for further investigation into the effects of various washing processes on denim fabrics. Additionally, the findings offer valuable insights into optimizing denim fabric properties through targeted washing processes, paving the way for sustainable washing recipes and advancements in the denim industry.

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Conflicts of Interest

The author(s) declare no conflict of interest.

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