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Comparisons of fabric care performances between conventional and high-efficiency washers and dryers

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Abstract

High-efficiency (HE) washers use 35–50% less water and about 50% less energy per load than conventional washers. However, there has been a consistent debate as to whether HE washers perform better or worse in garment care than conventional washers. Consumers need research-based information that would help them make informed decisions concerning the purchase of a clothes washer. The purpose of this study was to compare fabric hand, appearance retention (strain removal, color change, and fabric smoothness), and dimension stability (dimensional change and skewness change) after the specimens were repeatedly washed and dried for up to 20 cycles in three combinations of washer and dryer used: (a) conventional washer and dryer, (b) HE washer and conventional dryer, and (c) HE washer and dryer. The results showed that the specimens washed in the HE washer had better fabric hand and were smoother (fewer wrinkles) than those washed in the conventional washer. Conventional and HE washers performed similarly in color change, dimensional change, and skewness change. In regard to dryer, all results except those for stain removal showed no significant differences between the specimens dried in the conventional dryer and those dried in the HE dryer. In stain removal, when a softener was not used, the conventional dryer removed more stains from the specimens than the HE dryer. However, when a softener was used, the stains on the specimens dried in the conventional dryer were more difficult to remove than those on the specimens dried in the HE dryer.

Keywords: Fabric care, High-efficiency, Washing machine, Fabric hand, Appearance retention, Dimension stability

Introduction

According to the Residential Energy Consumption Survey reported by the United States Energy Information Administration (2009), 93.2 million households (82.0% of households) in the United States (US) had clothes washers and 90.2 million households (79.4% of households) had clothes dryers. Residential laundry appliances, especially clothes washers, are important not just in US households. Ownership rates of clothes washer in many countries are higher than that in the US (e.g., South Korea 100%, Japan 99%, Australia 97%, and West European countries 94%; Pakula and Stamminger 2010).

Most residential clothes washers in the US and Asia have been traditionally top-loading, vertical-axis washers (Pakula and Stamminger 2010). As estimated by Tomlinson

and Rizy (1998), top-loading, vertical axis washers use an average of over 40 gallons of water and over 7700 British thermal units (Btu) of energy per load of laundry. From these averages, the authors estimated that nearly 1.4 trillion gallons of water and 270 trillion Btu of energy were used by these vertical axis washers annually nationwide. Clothes dryers are also significant energy users. According to the Annual Energy Outlook reported by the United States Energy Information Administration (2016), clothes dryers in the US consumed 660 trillion Btu of energy in 2015.

Because large amounts of water and energy are used with each load of clothing washed, the growth in environmental awareness has increased the concern for water and energy conservation related to the home laundry process. Consequently, high-efficiency (HE) washers, which have been commonly used in Europe, became more widely available in the US by the late 1990s (Building 1997). According to the United States Environmental Protection Agency, Energy Start (2012), HE washers use 35–50% less water and about 50% less energy per load than conventional clothes washers. However, conventional washers are cheaper than HE washers. According to Hustvedt et al. (2013), cost is one of the main reasons why current owners of conventional washers do not want to purchase a HE washer.

According to *USA Today*, HE washers became popular among US consumers in the late 2000s (Wroclawski 2014); about 45% of washers sold in the US in 2009 were HE washers. However, the sales of HE washers in 2014 dropped to 29.5% because of the higher cost and the debate as to whether HE washers perform better. Manufacturers' advertisements claim that these new technologies provide real benefits, including not only water, energy and money saving, but also better performance in garment care. However, limited academic studies were found on the comparisons of conventional washers and dryers with HE ones in fabric care performance to help consumers determine whether these advertisement claims are truthful and whether it is worth paying a higher price for a HE washer and dryer. Consumers need research-based information that would help them make informed decisions concerning the purchase of a clothes washer and dryer.

To fill this void, the purpose of this study was to compare the fabric hand, appearance retention (i.e., strain removal, color change, and smoothness), and dimension stability (i.e., dimensional change and skewness change) after the specimens were washed and dried for 1, 5, 10, 15, and 20 cycles under three combinations of washer and dryer used: (a) washed in a conventional washer and dried in a conventional dryer, (b) washed in a HE washer and dried in a conventional dryer, and (c) washed in a HE washer and dried in a HE dryer. The condition "washed in a HE washer and dried in a conventional dryer" was included in the study because some consumers may consider replacing a HE washer but keeping the conventional dryer. In addition, because over 60% of US households regularly use dryer sheet softeners in the home laundry process (American Association on Textile Chemists and Colorists (AATCC) 2012), a dryer sheet softener group and a control group (no softener) were included in the research design to examine if using a dryer sheet softener plays a role in the fabric care performance of the washer and dryer combinations.

Literature review

Residential clothes washers

The residential clothes washer was introduced to the US market in the 1920s, but fully automated washing machines, which filled and drained water automatically and spun clothes to reduce the amount of water left after rinsing, were not available until the late 1930s (Shehan and Moras 2006). Since the 1940s, the sales of home laundry appliances have grown dramatically (Stawreberg 2011). According to the United States Energy Information Administration (2009), 82.0% of US households have clothes washers, and the households that own a clothes washer do two to nine laundry loads each week, resulting in an average of 400 washing loads per year.

Conventional vertical-axis clothes washers

Conventional *vertical-axis clothes* washers are top-loading washers with a vertically mounted tub that contains an agitator at the center of the drum. During the washing cycle, the tub will be filled with water, and the agitator will rotate or pulse, turning the clothes around in the water to clean them. Conventional washers use a large amount of water per load, allowing the clothes to easily float and move in the detergent solution. Because energy is required to heat the water, conventional washers use a vast amount of energy as well as water (Bansal et al. 2011). However, conventional washers are sold for a lower price and complete a washing cycle faster than HE washers (Consumer Reports 2012).

High-efficiency (HE) clothes washers

There are two types of HE clothes washers in the US market, the front-loading, horizontal-axis HE washer and the top-loading, vertical axis HE washer. Front-loading HE washers represent about 90% of the HE washing machine market in the US (Healthy House Institute 2010). Front-loading HE washers require less water for washing because the tub is typically filled only one-third or one-half full of water. These washers use the horizontal axis to create a tumbling action, rotating clockwise and counterclockwise to tumble the laundry items back and forth through a small pool of water. The rotating motion flexes the weave of the fabrics and forces water and detergent through each garment, removing soils with the use of less mechanical agitation than that used by conventional washers. Top-loading HE washers differ from the conventional top-loading type in that there is an agitating plate at the bottom of the tub instead of a vertical agitator midway between the top and bottom of the tub. The cleaning action occurs as the plate bounces the clothes in a small amount of water.

In addition to saving water, HE washers can also save energy. As much as 80–90% of the energy used by washers is for heating the water used in the washing cycle (Electric Power Research Institute 2010). Because less water is required in HE washers, if the garments are washed in either hot or warm water, less energy is needed to heat the water. Another energy saving benefit of HE washers is a shorter drying time. Since HE washers have a significantly higher spin speed than conventional washers, water can be extracted more effectively. Less water means a shorter drying time after washing, resulting in energy cost savings of as much as 50% (United States Environmental Protection Agency, Energy Start 2012). According to ENERGY STAR, a program developed by the United

States Environmental Protection Agency, Energy Star (2017), which promotes energy efficiency in products, a HE clothes washer needs to use at least 33% less water and 28% less energy than the minimum efficiency standards required by conventional washers to be able to carry the ENERGY STAR logo.

Another advantage of HE washers is that it requires less detergent, since less water is used for the laundry process, thus reducing the environmental impacts of detergents such as surfactant toxicity (Hill 2015). However, detergents specifically designed for HE washers need to be used. Such detergents are formulated to create a small amount of suds and be able to be dispersed quickly in low water volume machines. In addition, the tumble action of HE washers usually creates more suds than a conventional agitator action due to the interaction of the tumbling water and detergent (American Association on Textile Chemists and Colorists (AATCC) 2012). Therefore, the amount of water used by HE washers cannot sufficiently clean out the suds created by a traditional detergent.

Studies on comparisons of conventional and HE washers

Limited academic studies on the comparisons of conventional and HE washers have been published in research journals. One study of interest was conducted by Klausing et al. (2012), who compared a conventional top-loading washer and a HE front-loading washer in dimensional change of knit fabrics after five laundering cycles. One laundering cycle includes one washing cycle and one drying cycle. The same tumble dryer was used to dry the specimens washed in the conventional and the HE washer. Their results showed no significant differences in dimensional change between the fabrics washed in the two types of washers.

Schlag and Ordonez (2010) presented their study at a conference, reporting the comparisons of several care performances (appearance smoothness, dimensional change, color change, skewness change, and stain removal) of woven and knitted fabrics between washed in a conventional top-loading washer and a front-loading HE washer after five laundering cycles. For the woven fabric, the HE washer had better performance in appearance smoothness than the conventional washer, but no significant difference in appearance smoothness was found for the knit fabric. In addition, no significant differences were found in dimensional change and color change between the two types of washers for both the woven and the knit fabric. Schlag and Ordonez also reported some mixed results. A significant difference in skewness change was found for the woven test fabric after five laundering cycles, but no significant difference was found for the woven ballast fabric. (Ballast fabric was used to bring the total weight of the laundry load to a specified value, which was 4.00 ± 0.13 lb). In stain removal, spectrophotometric measurements of Delta E showed that the HE washer had better performance in removing used motor oil and mustard stains for both woven and knit fabrics, but the conventional washer had better performance in removing lipstick stains. However, the Gray Scale Color Change results were opposite to the spectrophotometric results; the conventional washer had better performance in removing used motor oil and mustard stains for both woven and knit fabrics, but the HE washer had better performance in removing lipstick stains.

Cotton Incorporated and Whirlpool Corporation published a study comparing (a) a conventional top-loading, vertical axis washer, (b) a front-loading, horizontal axis HE

washer, and (c) a top-loading, vertical axis HE washer for a cotton knit fabric after 20 laundering cycles (Ankeny et al. 2014). The authors indicated that the specimens washed in the two HE washers "seemed to have" less color change than the specimens washed in the conventional washer. Because statistical analysis was not used in the study, it is unclear if the findings were statistically different between the types of washers or within the sample/testing variance. The specimens washed in two HE washers had consistently lower degrees of shrinkage than those washed in the conventional washer after 5, 10, 15 and 20 laundering cycles. These findings were inconsistent with the results of Klausing et al. (2012) and Schlag and Ordonez (2010), who found no significant differences in shrinkage and color change after five laundering cycles. Among the few studies that compared conventional and HE washers (Ankeny et al. 2014; Klausing et al. 2012; Schlag and Ordonez 2010), many mixed findings were reported, indicating an essential need for further studies.

Residential clothes dryers

Residential clothes dryers were available in the early 1940s; however, they were expensive, and most families could not afford them. In 1955, only 10% of US households had one (Morris 2017). After 1955, companies were able to sell automatic clothes dryers at a much lower price; therefore, clothes dryer sales increased considerably. According to the United States Energy Information Administration (2009), 79.4% of US households have a clothes dryer (63.2% electric clothes dryer, 15.3% gas clothes dryer, and 0.9% propane clothes dryer). The averaged number of annual dryer loads varies in different households, but is estimated to be 439 (McCowan et al. 2015). However, using a clothes dryer is a habit peculiar to the US and Canada (81% in 2009; Statista 2017). Many Europeans and Asians who can afford to purchase clothes dryers still tend to hang clothes up to dry. It is possible that US consumers prefer convenience and time saving and worry that clothes hung outdoor will absorb environmental dust and/or car exhausts. Many people in other countries, however, consider having a clothes dryer a waste of energy and money. In addition, most households do not have enough room for both a washer and a dryer.

Tumble dryers have been most widely used in the US. They continuously draw in the cool, dry, ambient air around them, heat it, and then pass it through the tumbler, where moisture is absorbed from the clothes. The hot, humid air produced in the drying process is usually vented outside the house to make room for more cool, dry air to continue the drying process. This design does not recycle the heat put into the load and thus is considered environmentally wasteful.

To address this issue, new clothes dryer technologies, such as heat pumps, was introduced in Europe for more than 10 years (Meyers et al. 2010) and have recently become available in the US market (Evergreen Economics 2016). Heat pump clothes dryers cool the warm, moist air produced in the drying process and condense the moisture into water. The cool, dry air is then heated and re-circulated back into the drum. Depending on the model, the manufacturers claim that heat pump dryers use 25–70% less energy than the average electric dryer. Consumer Reports (2015) tested a heat pump clothes dryer and found that the heat pump clothes dryer used about 40% less electricity, but took 112 min to dry a 12-pound load, 38 min longer than the time used in a regular

clothes dryer. Heat pump clothes dryers are not popular among US consumers, with a market share of almost zero (Evergreen Economics 2016). Meyers et al. (2010) found that heat pump clothes dryers had economic benefits only for households with high clothes dryer usage (over 700 cycles per year), which were 6% of the sample households, or for households in regions with high electricity price (i.e., the Northeast of the US and California) after about 500 cycles of usage per year. Another study, conducted by Martin et al. (2016), found that although the heat pump clothes dryer used less electricity than a conventional dryer, it released significantly more heat than a conventional dryer, leading to an increase of energy used to cool the house.

In the US market, almost all the clothes dryers paired with a HE clothes washer are still tumble dryers. However, some of these dryers do save energy by using more accurate moisture sensors than those used in conventional dryers to better detect the dampness of the laundry and shut off the machine when the clothes are dry (Consumer Reports 2015). In this way, energy can be saved and the clothes will not be over dried. Many of these dryers also use low heat and long drying times to save energy. However, the money saved from a HE dryer may not be significant according to consumer Reports (2015). A dryer with an ENERGY STAR label may save about $20 a year in electricity compared with the conventional dryers. However, the longer drying time means that more indoor air is drawn by the dryer and moved from the house through the vent to the outside after the drying process. This air movement may increase the energy of heating or cooling the house. Therefore, the net money saving from a HE dryer may be minimal.

Residential fabric softeners

The synthetic detergents used in a clothes washer can clean clothes effectively; however, they can also remove the fatty finish and lubricating waxes on the fabric when they remove dirt and oil, thereby changing the fabric hand of the washed garment (McCarthy and Drozdowski 1989). Fabric softeners were introduced to the US market in the early 1950s to provide a pleasant odor and improve the hand of laundered clothes (Simpson 1958). Fabric softeners can make the washed fabric soft and smooth by coating the washed fabric with lubricants and humectants. Since the introduction of fabric softeners to the market, their use has grown continuously. Currently, most households (about 80%) in the US regularly use fabric softeners during home laundering (American Association on Textile Chemists and Colorists (AATCC) 2012).

Between the two common types of fabric softeners for home laundering (rinse cycle softener and dryer sheet softener), the dryer sheet softener is more popular in US households (over 60% of households) (American Association on Textile Chemists and Colorists (AATCC) 2012). Dryer sheet softeners, which were introduced to the US market in the early 1970s (Williams 1982), are fabric softeners saturated onto sheets of a nonwoven fabric or polyurethane foam. Compared with rinse cycle softeners, dryer sheet softeners provide better anti-static properties, air permeability retention, water absorbency retention, and whiteness retention (Chen-Yu et al. 2009; Williams 1982; Wilson 1987). Dryer sheet softeners also form smaller pills and have no effect on flammability (Chen-Yu et al. 2008; Chiweshe and Crews 2000). However, dryer sheet softeners tend to have uneven softener deposition and are less effective in softening fabrics (Williams

1982). Although many households use fabric softeners during home laundering, no study comparing conventional and HE washers has included a fabric softener.

Methods

Research design

A between-subject experimental design was developed with three combinations of washer and dryer used (conventional washer/dryer, HE washer/conventional dryer, and HE washer/dryer) × 2 softener settings (dryer sheet softener vs. no softener) × 5 selected laundering cycles (1, 5, 10, 15, and 20). This research design resulted in 30 experimental groups. A control group with no laundering was also included. For each experimental group, five replicate tests were conducted.

There were two reasons that we included the three combinations of washer and dryer used (conventional washer/dryer, HE washer/conventional dryer, and HE washer/dryer) in this study. First, Evergreen Economics Company (2016) reported that in large retailers, 50–70% of their clothes dryers were sold as a washer/dryer pair, such as conventional washer/dryer or HE washer/dryer, while in the regional and local retailers, 80–95% of the dryer sales were part of a paired purchase. Therefore, conventional washer/dryer and HE washer/dryer were included in the research design. Second, most manufacturers' advertising efforts were in promoting HE washers, claiming that HE washers not only save water, energy and money, but also provide better performance in garment care. However, HE washers are much more expensive than conventional ones. Rather than buying a washer and dryer set, consumers may want to purchase a HE washer but keep their conventional dryer. To examine if it is a good option to purchase only a HE washer but use a conventional dryer for laundry, we also included the combination of HE washer and conventional dryer. We did not include the combination of conventional washer and HE dryer because according to the report of Evergreen Economics (2016), when consumers purchase a new dryer as a stand-alone purchase, they typically try to match their current washer in capacity and overall aesthetics. If consumers currently have a conventional washer, they are most likely to purchase a conventional dryer rather than a HE dryer. In addition, HE dryers are much more expensive than conventional ones, and the money saved from a HE dryer may be limited (Consumer Reports 2015). Therefore, the money savings from a HE dryer may not be adequate to cover the higher price paid for a HE dryer than for a conventional one.

Materials

Test fabric

Most previous studies used knit fabrics to compare the performance of conventional and HE washers (Ankeny et al. 2014; Klausing et al. 2012). Schlag and Ordonez (2010) used both knit and woven fabrics and found that the differences between the two types of washers were mostly in the woven fabric. Therefore, in the current study, an 100% cotton, plain weave, black fabric was used as the test fabric. Dark color fabrics are more vulnerable to the problem of fading than light color fabrics during the laundering process (Fergusson 2008); therefore, a black test fabric was selected to examine the color change after washing (color fastness to washing). The fabric weight was 112.15 g/m^2, which was measured according to ASTM D3776/D3776M-09a (2013): Standard Test Method for Mass per

Unit Area (Weight) of Fabric. The fabric count was 76 × 67, which was measured according to ASTM D3775-12: Standard Test Method for Fabric Count of Woven Fabric.

Specimen preparation

The test methods used in the current study require the use of two or three specimens for each experimental group (AATCC Test Methods 124-2011, 135-2010, and 79-2010 require three specimens; Test Method 130-2010 requires two). To increase the precision of the results, five specimens (five repeats) were used for each experimental group. Five specimen cutting diagrams were prepared to ensure that the five test specimens for each experimental group did not contain the same warp or filling yarns. No specimen was taken nearer than 6.5 cm (2.5 in.) from the fabric selvage edge (Merkel 1991). All specimens were cut to the size of 38 × 38 cm (15 × 15 in.) according to AATCC Test Methods 124-2011, 130-2010, 135-2010, and 179-2010.

Procedures

Laundry

The test fabrics were laundered according to AATCC Test Method 124-2011: Smoothness Appearance of Fabrics after Repeated Home Laundering. Tide® "2 × Ultra Free" (2 × means no dyes and unscented) regular liquid laundry detergent was used in the conventional washer, and Tide® "2 × Ultra Free" HE laundry detergent was used in the HE washer. The reasons for selecting these detergents are (a) Tide® has the largest market share in the US (Statistia 2017b), (b) Tide® was the most commonly used laundry detergent in previous studies (Ankeny et al. 2014; Chen-Yu et al. 2008, 2009; Schlag and Ordonez 2010), and (c) "2 × Ultra Tide® Free" detergents were available for both conventional washers and HE washers. The dryer sheet softener "Ultra® Gain Joyful Expressions Apple Mango Tango dryer sheet" was selected based on the highest rating for dryer sheet fabric softener brands according to Consumer Reports (2008).

A conventional top-load vertical axis washer with an agitator (i.e., MAYTAG Automatic Washer Model A806), a conventional top-load tumble dryer (i.e., MAYTAG Automatic Tumble Dryer Model DE806), a HE front-loading horizontal axis washer with tumble action (i.e., Whirlpool® Duet Sport® Front-Loading Washer Model WFW8300S), and a HE front-loading dryer (i.e., Whirlpool® Duet Sport® Front-Loading Dryer Model WED8300S) were used in the study. Similar washer and dryer settings were used for the conventional and HE washers and the conventional and HE dryers, respectively. The conventional washer was set on regular wash, regular spin, warm wash, warm rinse, and normal water level. The HE washer was set on normal/casual wash, medium speed spin, and warm wash conditions. The conventional clothes dryer was set on the "regular" setting, and the HE clothes dryer was set on the "normal" setting.

Test methods

Fabric hand, stain removal, color change, fabric smoothness, dimensional change, and skewness change were examined in the current study. Because the assessments of fabric hand, stain removal, color change, and fabric smoothness were subjective evaluations, to reduce the effect of human errors or bias, we used three evaluators in the assessment process. These evaluators were graduate students in clothing and textiles and were

trained before conducting the tests and evaluations. Five replicate tests were conducted for each experimental group. One specimen was used for each test, and therefore five specimens were used for each experimental group. The three evaluators rated all the specimens independently. In the data analysis, for each specimen, the average of the ratings from the three evaluators was used.

Fabric hand (sensation of a fabric assessed by touch) was measured according to AATCC Evaluation Procedure 5-2011: Fabric Hand: Guidelines for the Subjective Evaluation. An unwashed fabric was used as the standard. Each specimen was compared with the standard and ranked from "much rougher than the unwashed fabric" (1), to "as the unwashed fabric" (3), to "much softer than the unwashed fabric" (5).

Three types of appearance retention properties were measured—stain removal, color change, and fabric smoothness. AATCC Test Method 130-2010: Soil Release: Oily Stain Release Method was used as a guideline to conduct the test for stain removal. Six types of stains (i.e., vegetable oil, mustard, spaghetti sauce, lipstick, nail polish, and white paint) were used to represent the common stains found in home laundering. The staining procedure for vegetable oil, mustard, and spaghetti sauce followed AATCC Test Method 130-2010. For lipstick, nail polish, and white paint, to increase the consistency of the stains on the specimens, a stained specimen was established as a standard for each type of stain, and one person was responsible for staining one type of stain for all test specimens based on the standard. As in the study by Schlag and Ordonez (2010), the Gray Scale for Color Change was used to evaluate the color change after washing from the color of the stained, unwashed standard specimen. On this scale, "5" indicates no color change (i.e., the stain has not been removed at all) and "1" indicates a severe color change (i.e., the stain has been completely removed).

For color change, AATCC Evaluation Procedure 9-2011: Visual Assessment of Color Change of Textiles was followed, and the Gray Scale for Color Change was used to evaluate the color change after washing from the color of the unwashed fabric, where "5" indicates no color change and "1" indicates a severe color change. Fabric smoothness was measured according to AATCC Test Method 124-2011: Appearance of Fabrics after Home Laundering. The washed specimens were compared with the AATCC Three-Dimensional Smoothness Appearance Replicas. "5" corresponded to the smoothest appearance and "1" corresponded to the most wrinkled appearance.

Dimensional change and skewness change were measured to evaluate the dimensional stability. The dimensional change of a specimen was measured according to AATCC Test Method 135-2010: Dimensional Changes of Fabrics after Home Laundering. The percent dimensional change in the warp and filling directions were calculated. Because a fabric may shrink in the warp direction but grow in the filling direction, to better understand the dimensional stability of the fabric as a whole, instead of analyzing the warp and filling directions separately, the dimensional change was calculated by the average of the percent shrinkages in the warp and filling directions, consistent with the method of Klausing et al. (2012). The percent skewness change was measured according to AATCC Test Method 179-2010: Skewness Change in Fabric and Garment Twist Results from Automatic Home Laundering.

Table 1 Three-way analysis of variance for fabric hand

Fabric hand	Sum of squares	*df*	Mean square	*F*
Main effects	15.78	35	.45	5.71***
Combination of washer and dryer (W/D) used	3.06	2	1.53	19.39***
Softener usage	1.28	1	1.28	16.19***
Number of laundering cycles	9.39	5	1.88	23.80***
Combination of W/D used × softener	.14	2	.07	.89
Combination of W/D used × cycles	1.27	10	.13	1.61
Softener × cycles	.35	5	.07	.89
Combination of W/D used × softener × cycles	.29	10	.03	.37
Error	11.37	144	.08	
Total	1644.23	180		

*** $p < .001$

Table 2 Mean differences in fabric hand and fabric smoothness by three combinations of washer and dryer used

	Washer/dryer used						*F*
	Conventional washer/dryer		HE washer/ conventional dryer		HE washer/HE dryer		
	Mean	SD	Mean	SD	Mean	SD	
Fabric hand	2.82[b]	.36	3.03[a]	.36	3.14[a]	.36	8.32***
Fabric smoothness	2.35[b]	.05	2.70[a]	.05	2.83[a]	.05	14.39***

Fabric hand was evaluated by a rating of 1 to 5. "5" indicates "much softer than the standard unwashed fabric," "3" indicates "as the standard unwashed fabric," and "1" indicates "much rougher than the standard unwashed fabric"

Fabric smoothness was evaluated by a rating of 1 to 5. "5" indicates the best performance (i.e., smooth without any wrinkle)

*** $p < .001$

a, b Means with different letters are significantly different at .05 level according to the test of Tukey Honest Significant Difference

Results and discussion

For each fabric care performance, a three-way ANOVA was used to analyze the effects of three independent variables (i.e., different combinations of washer and dryer used, usage of a dryer sheet softener, and number of laundering cycles) and their interactions. Tukey Honest Significant Difference (Tukey HSD) was used to conduct post hoc multiple comparisons of group means.

Fabric hand

No previous study has been found comparing conventional and HE washers in fabric hand. Results of the current study show that there are significant differences between the different combinations of washer and dryer used ($F(2180) = 19.39$, $p < .001$; see Table 1). The results of Tukey HSD show that the specimens washed in the HE washer have significantly better fabric hand than those washed in the conventional washer ($p < .001$; see Table 2). Figure 1 shows the ratings of fabric hand with no softener and with a dryer sheet softener. The lowest line in either figure shows the ratings of the specimens washed in the conventional washer, indicating that the fabric hand of these specimens are consistently rougher than those washed in the HE washer, regardless of the number of the cycles (i.e., 1, 5, 10, 15, and 20)

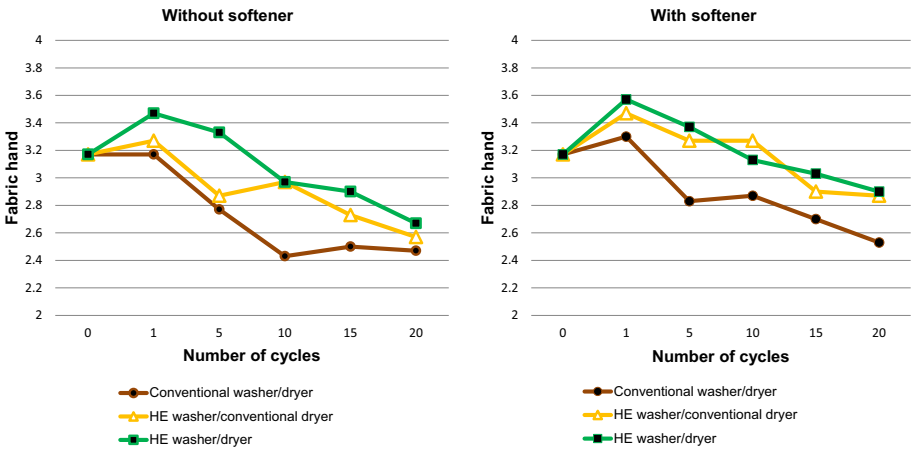

Fig. 1 Fabric hand without and with a dryer sheet softener

and whether a softener is used or not. The results of Tukey HSD show that for all the specimens washed in a HE washer, there is no significant difference in fabric hand between the specimens dried in the conventional dryer and those dried in the HE dryer. These results indicate that the differences in fabric hand are mainly caused by the washers (conventional vs. HE), rather than the dryers. As expected, repeated washing makes the specimens rougher ($F(5, 180) = 23.80$, $p < .001$; see Table 1), and the use of softener significantly improves the fabric hand ($F(1, 180) = 16.19$, $p < .001$; see Table 1). Figure 1 shows that the fabric hand of specimens dried with a softener is consistently higher than that of specimens dried without a softener in each of the combinations of washer and dryer used.

Appearance retention

Stain removal

Six types of stain (i.e., white paint, vegetable oil, mustard, spaghetti sauce, lipstick, and nail polish) were used in this study. After one laundering cycle, all types of stain except white paint are removed with no visual residual. These results differ from the findings of Schlag and Ordonez (2010). Analyzing the Gray Scale for Color Change values, Schlag and Ordonez found that the conventional washer showed better performance in removing used motor oil and mustard stains, but the HE washer showed better performance in removing lipstick stains. In the current study, all types of stain except white paint are successfully removed after one wash by both types of washers. It is possible that because the test fabric used in this study is black, a slight stain residual is not prominent for the human eyes to detect.

As expected, the number of laundering cycles has a significant effect on the removal of white paint stains ($F(5, 180) = 264.74$, $p < .001$; see Table 3). The results of Tukey HSD show that continuous washing removes the white paint stains. Significant amounts of white paint stains are removed after 1, 5, and 10 laundering cycles. There is no significant difference in stain removal between 10 cycles and 15 cycles, but significantly more white paint stains are removed after 20 cycles than after 10 cycles (see Table 4). The combination of washer and dryer used or softener usage has no significant effect; however, a

Table 3 Three-way analysis of variance for stain removal

Stain removal	Sum of squares	*df*	Mean square	*F*
Main effects	285.27	35	8.15	38.91***
Combination of washer and dryer (W/D) used	.37	2	.18	.87
Softener usage	.20	1	.20	.94
Number of laundering cycles	277.27	5	55.45	264.74***
Combination of W/D used × softener	1.62	2	.81	3.88*
Combination of W/D used × cycles	3.11	10	.31	1.48
Softener × cycles	.63	5	.13	.60
Combination of W/D used × softener × cycles	2.08	10	.21	.99
Error	30.16	144	.21	
Total	1497.66	180		

* $p < .05$; *** $p < .001$

significant interaction is found between these two factors ($F(2, 180) = 3.88$, $p < .05$; see Table 3). Figure 2 shows that with no softener used, more white paint stains are removed from the specimens dried in the conventional dryer than from the specimens dried in the HE dryer, regardless of the type of washer (see Fig. 2). However, with the use of softener, for the specimens washed in the HE washer, less white paint stains are removed from the specimens dried in the conventional dryer than from the specimens dried in the HE dryer. Consumer Reports (2015) reported that many HE dryers use low heat and long drying times to save energy. Although no temperature information was provided by the manufacturers of the dryers used in the current study, the drying time per load was found to be 10–15 min longer in the HE dryer than in the conventional dryer. It is possible that the conventional dryer in the study had a higher temperature than the HE dryer and therefore could dry the laundry load faster. When a softener was not used, this higher temperature could help remove more white paint stains. However, when a dry sheet softener was used, it coated the white paint stains, and the high heat in the conventional dryer could make the softener chemically bond to the stains, hindering the water from going into the fabric to remove the stains.

Color change

No significant difference in color change is found between the different combinations of washer and dryer used (see Table 5), consistent with the findings of Schlag and Ordonez (2010). The use of a dryer sheet softener has no significant effect on color change. Only the number of laundering cycles has a significant effect on color change ($F(5, 180) = 40.48$, $p < .001$). The results of Tukey HSD show that the most significant color change occurs after one laundering cycle and then after 20 laundering cycles (see Table 4).

Fabric smoothness

Significant differences in fabric smoothness are found between different combinations of washer and dryer used ($F(2, 180) = 28.59$, $p < .001$; see Table 6). The results of Tukey HSD show that the specimens washed in a HE washer are significantly smoother than those washed in a conventional washer (see Table 2). Figure 3 shows that regardless of the type of dryer used and the number of laundering cycles, the ratings of the specimens washed

Table 4 Mean differences in stain removal, color change, fabric smoothness, dimensional change, and skewness change by laundering cycles

	Laundering cycles												*F*
	0		1		5		10		15		20		
	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	
Stain removal	5.00[a]	.08	3.23[b]	.08	2.17[c]	.08	1.68[d]	.08	1.55[de]	.08	1.37[e]	.08	19.31***
Color change	5.00[a]	.07	4.06[b]	.07	4.09[b]	.07	4.01[b]	.07	3.93[bc]	.07	3.67[c]	.07	47.17***
Fabric smoothness	3.28[a]	.06	2.52[b]	.06	2.48[b]	.06	2.47[b]	.06	2.47[b]	.06	2.53[b]	.06	21.27***
Dimensional change (%)	0.00[a]	.11	−4.39[b]	.11	−4.71[bc]	.11	−4.92[c]	.11	−5.07[c]	.11	−5.07[c]	.11	416.90***
Skewness change (%)	0.00[a]	.21	1.26[b]	.21	1.30[b]	.21	1.52[b]	.21	1.42[b]	.21	1.58[b]	.21	9.84***

Stain removal was evaluated by a rating of 1 to 5. "5" indicates the worst performance (i.e., no color change; stains not removed at all)

Color change and fabric smoothness were evaluated by a rating of 1 to 5. "5" indicates the best performance (i.e., no color change or no wrinkle at all)

*** $p < .001$

a, b, c, d, e Means with different letters are significantly different at .05 level according to the test of Tukey Honest Significant Difference

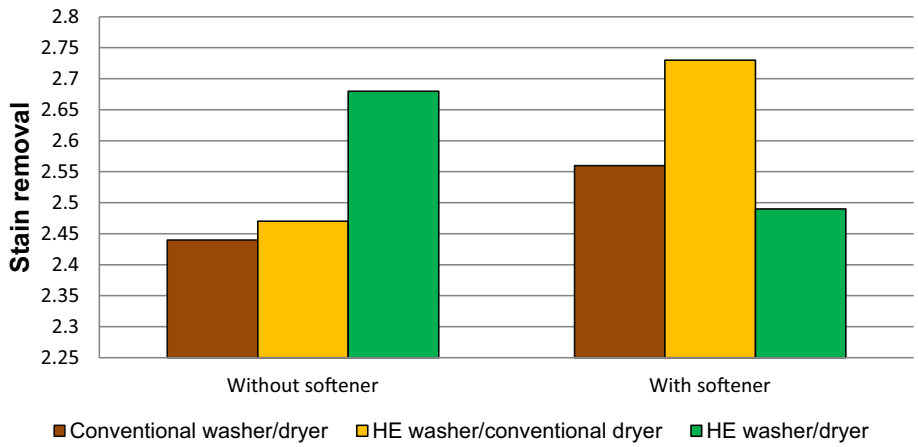

Fig. 2 Stain removal without and with a dryer sheet softener. A smaller number indicates better performance of stain removal (i.e., more color change; more stains removed)

Table 5 Three-way analysis of variance for color change

Color change	Sum of squares	*df*	Mean square	*F*
Main effects	35.28	35	1.01	6.59***
Combination of washer and dryer (W/D) used	.50	2	.25	1.64
Softener usage	.19	1	.19	1.24
Number of laundering cycles	30.99	5	6.20	40.48***
Combination of W/D used × softener	.03	2	.01	.09
Combination of W/D used × cycles	1.76	10	.18	1.15
Softener × cycles	1.64	5	.33	2.15
Combination of W/D used × softener × cycles	.18	10	.02	.12
Error	22.04	144	.15	
Total	3120.14	180		

*** $p < .001$

Table 6 Three-way analysis of variance for fabric smoothness

Fabric smoothness	Sum of squares	*df*	Mean square	*F*
Main effects	27.74	35	.79	6.35***
Combination of washer and dryer (W/D) used	7.14	2	3.57	28.59***
Softener usage	.15	1	.15	1.19
Number of laundering cycles	15.78	5	3.16	25.30***
Combination of W/D used × softener	.05	2	.02	.19
Combination of W/D used × cycles	1.69	10	.17	1.35
Softener × cycles	.97	5	.19	1.55
Combination of W/D used × softener × cycles	1.97	10	.20	1.58
Error	17.97	144	.13	
Total	1285.25	180		

*** $p < .001$

in the HE water are consistently higher than those of the specimens washed in the conventional washer. Of the specimens washed in the HE washer, there is no significant difference in fabric smoothness between the specimens dried in the conventional dryer and

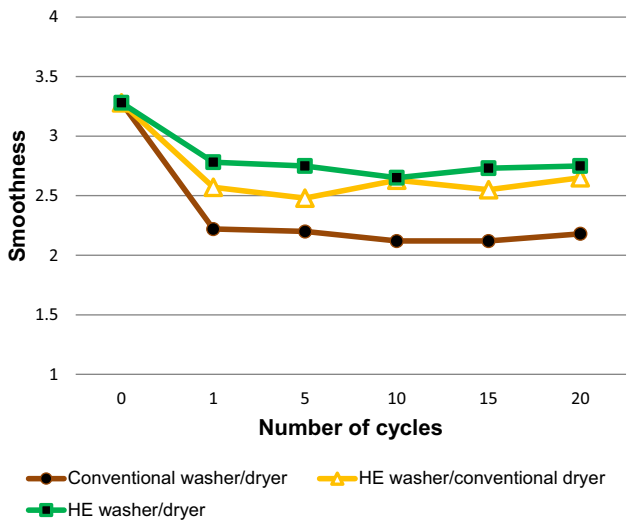

Fig. 3 Fabric smoothness as a function of number of laundering cycles for different combinations of washer and dryer used

those dried in the HE dryer (see Table 2). These results indicate that the differences in fabric smoothness are caused by the washers (conventional vs. HE), rather than the dryers, consistent with the findings of Schlag and Ordonez (2010). The use of a softener has no significant effect on fabric smoothness (see Table 6). The number of laundering cycles has a significant effect on fabric smoothness ($F(5, 180) = 25.30$, $p < .001$). The results of Tukey HSD show that differences are found only between unwashed and washed specimens (see Table 4). The unwashed specimens are significantly smoother than the washed specimens, but further repeated washing (5, 10, 15, and 20 laundering cycles) has no significant effect on fabric smoothness.

Dimensional stability

Dimensional change

Klausing et al. (2012) and Schlag and Ordonez (2010) found no significant difference in dimensional change between the specimens washed in a conventional washer and those washed in a HE washer after five laundering cycles. The results of the current study confirm these findings and show that there is no significant difference in dimensional change between the different combinations of washer and dryer used even after 20 laundering cycles (see Table 7). The use of a dryer sheet softener has no significant effect on dimensional change. Only the number of laundering cycles has a significant effect on dimensional change ($F(5, 180) = 346.47$, $p < .001$). The results of Tukey HSD show that the most significant shrinkage occurs after one laundering cycle and further significant residual shrinkage is found after 10 laundering cycles (see Table 4).

Skewness change

There is no significant difference in skewness change between the combinations of washer and dryer used (see Table 8). This result is different from the findings of Schlag

Table 7 Three-way analysis of variance for dimensional change

Dimensional change (%)	Sum of squares	*df*	Mean square	*F*
Main effects	601.53	35	17.19	50.20***
Combination of washer and dryer (W/D) used	.91	2	.45	1.32
Softener usage	.05	1	.05	.14
Number of laundering cycles	593.13	5	118.63	346.47***
Combination of W/D used × softener	.28	2	.14	.41
Combination of W/D used × cycles	2.05	10	.21	.60
Softener x cycles	.97	5	.19	.57
Combination of W/D used × softener × cycles	4.14	10	.41	1.21
Error	49.30	144	.34	
Total	3567.86	180		

*** $p < .001$

Table 8 Three-way analysis of variance for skewness change

Skewness change (%)	Sum of squares	*df*	Mean square	*F*
Main effects	79.89	35	2.28	1.75*
Combination of washer and dryer (W/D) used	.27	2	.13	.10
Softener usage	.01	1	.01	.01
Number of laundering cycles	52.37	5	10.47	8.04***
Combination of W/D used × softener	3.30	2	1.65	1.27
Combination of W/D used × cycles	18.25	10	1.83	1.40
Softener × cycles	3.61	5	.72	.55
Combination of W/D used × softener × cycles	2.09	10	.21	.16
Error	187.62	144	1.30	
Total	517.85	180		

*** $p < .001$

and Ordonez (2010), who found a significantly greater skewness change in the specimens washed in a conventional washer than in the specimens washed in a HE washer. One possible reason for the difference between the findings of these two studies is the washer setting. In both studies, the HE washers were set on normal/casual wash. However, the settings of conventional washers were different. In the study of Schlag and Ordonez, the conventional washer was set to "Ultra Clean" and agitation and spin speed were set to "Heavy Duty". In the current study, the settings of the conventional washer were more compatible with the settings of the HE washer, which were regular wash and regular spin. The extreme agitation in the conventional washer in the study of Schlag and Ordonez might increase the twist of the fabric, causing a higher skewness change. The results also show that the presence of a dryer sheet softener has no significant effect on skewness change. In the current study, only the number of laundering cycles has a significant effect on skewness change ($F(5, 180) = 8.04$, $p < .001$). The results of Tukey HSD show that the specimens skew significantly after the first laundering cycle, but further repeated washing (5, 10, 15, and 20 laundering cycles) has no significant effect on skewness change (see Table 4).

Conclusion and implication

The purpose of this study is to compare fabric care performances (i.e., fabric hand, appearance retention, and dimensional stability) after the specimens have been repeatedly washed and dried for up to 20 cycles in three combinations of washer and dryer used (i.e., conventional washer/dryer, HE washer/conventional dryer, and HE washer/dryer). The results showed that the specimens washed in a HE washer had better fabric hand and smoothness. These results suggest that the HE washer was gentler to the washed clothes because it created less mechanical agitation during the wash process than the conventional washer. Although the agitation in the HE washer was less than that in the conventional washer, according to the current study, the washing action was sufficient to remove most stains, except white paint, after one laundering cycle. The effectiveness the HE washer in removing white paint was similar to that of the conventional washer. The current study also showed that the conventional and HE washers performed similarly in color change, dimensional change, and skewness change.

All results except those on stain removal showed that there were no significant differences between the specimens dried in the conventional dryer and those dried in the HE dryer when all the specimens were washed in the HE washer. A significant interaction was found in stain removal between the combination of washer and dryer used and the use of softener. When a softener was not used, the conventional dryer removed more stains from the specimens than the HE dryer. However, when a softener was used, among the specimens washed in the HE washer, the stains on the specimens dried in the conventional dryer were more difficult to remove than the specimens dried in the HE dryer.

The results of the current study provide research-based information to verify manufacturers' advertisement claims and help consumers make an informed decision in the purchase of a clothes washer or dryer. The findings of the current study suggest that buying a HE washer is a wise decision because it performs better in fabric hand and fabric smoothness, as well as water and energy savings. Although the initial cost of a HE washer is higher than that of a conventional washer, according to Hamm (2011) calculation, in six and half years, the savings from less energy and water use in a HE washer can pay for the price difference. This calculation was based on 400 washing loads per year, the number of loads for an average American family (United States Environmental Protection Agency, Energy Start 2012). For consumers who do more frequent washing, the savings will add up more quickly. A HE washer may be a smart choice in cost saving alone because the average life expectancy of a new washing machine is 11 years (Vogt 2015). In addition to money saving, evidence shows that environmental resources are limited and the concept of sustainability is important. All the choices or actions that we, as consumers, make today will influence the supply of resources in the future. Furthermore, HE washers require less detergent and thus reduce the environmental impacts of detergents. When making a purchase decision for a clothes washer, we need to realize that our decisions at present will influence the environments of generations to come.

The current study showed that a HE dryer did not significantly improve laundry performance. In addition, according to Meyers et al. (2010), even the most energy-efficient heat pump dryers had economic benefits only for households with high clothes dryer usage. A consumer who does not use a clothes dryer much and has limited resources

may consider purchasing a HE washer but keeping the conventional dryer. However, when using a HE washer and a conventional dryer for laundry, consumers need to note that HE washers have a significantly higher spin speed than conventional washers. More water can be extracted and the drying time may be shorter. Consumers may need to check whether the usual drying setting would over-dry the laundry load. In addition, the current study showed that when a softener was used, the conventional dryer seemed to hinder the removal of stains. When using a conventional dryer, consumers should not use a softener when they see residual stains, which can be removed only by repeated laundering.

Limitation and recommendations for future studies

Several limitations of the study were recognized and may be examined through further research. First, although many brands of washers are available on the market, only one conventional washer and one front-loading HE washer were used in the study. The wash action and setting of each washing machine may differ. More tests involving various washers are needed to verify the effects of washer on fabric care performances. Second, only a plain weave fabric was used in the current study, but different fabrics may behave in a different way when washed in different types of washers. Further studies using other types of fabric structures, such as knits or woven fabrics with other types of weaves (e.g., twill or satin weave), may be carried out. Third, only a black fabric was used in the current study. Although a fabric in a dark color was a better choice in comparing color change after washing, a black fabric might make the differences in stain removal harder to detect. Further studies may consider using a lighter color to verify the findings of stain removal in the current study. Fourth, only one type of laundry detergent and one type of dryer sheet softener were used. Chowdhary (2017) reported that a significant difference was found in dimensional stability between an AATCC standard detergent and a commercial detergent. Further studies may need to use different types of detergents or softeners to fully understand the role a detergent or softener plays in the fabric care performance of conventional and HE washers.

Authors' contributions
JHCY and JAE designed and carried out the study, drafted the manuscript, and participated in the sequence alignment. Both authors read and approved the final manuscript.

Competing interests
The authors declare that they have no competing interests.

Ethical approval and consent to participate
Not applicable.

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