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Performance evaluation of water-repellent combat uniforms using a static manikin and human subjects under a rainfall tower system

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Abstract

The purpose of the present study was to evaluate the water-repellent properties of newly-developed combat uniforms using a rainfall tower system. Two types of water-repellent- combat uniforms with an identical level of water repellency through textile tests (WR_M and WR_T) were compared with an untreated-combat uniform (Control). A static manikin was used to evaluate water-repellent properties in a standing position and eight male subjects participated to test walking effects under artificial rainfall. The results showed that it took to saturate the upper body was longer for WR_T than WR_M and Control in the standing position for both normal and heavy rain conditions ($P < 0.05$). The lower body in WR_T was rarely wet in the standing position after 60 min, whereas the lower body was partially wet while walking within 30 min. Changes in clothing weight after the rainfall test were 729 ± 21, 256 ± 36 and 137 ± 25 g per trial for Control, WR_M, and WR_T, respectively ($P < 0.001$). Subjects expressed better tactile, less colder, less heavier, and less humid sensations and less uncomfortable feeling for WR_T than Control or WR_M ($P < 0.05$), while WR_M was better only for tactile sensation and heaviness than Control ($P < 0.05$). Ten-time-washes had not impaired the water-repellent properties of WR_M or WR_T. These results indicated that the rainfall tower test is valid to verify water-repellent property of clothing ensemble and suggest a possibility of classifying the water repellency of clothing ensemble into sub-levels of an excellent and a fair class. Further studies on wider range of experimental conditions to validate the current results are required.

Keywords: Water repellency, Combat uniforms, Thermal comfort, Rainfall tower, BS EN 14360, Technical wear design, Clothing ergonomics

Introduction

While basic physical properties, such as tensile strength, abrasion resistance, flexibility, thickness, stiffness, launderability, camouflaging, colour fastness, or air permeability, are tested as requirements of ordinary combat uniforms, water repellency is not yet required for Korean combat uniforms (KDS 8305-3012, 2018). Instead, a military raincoat is provided in case of rains. Water repellency for combat uniforms has been studied by the NSRDEC (The Natick Labs) in the US. In general, water-repellent fabrics have been used for sportswear, personal protective equipment, firefighters' clothing, outdoor work wear, car covers, and medical bedding. Lowering the surface tension of base textiles by means of a fluorine-rich or fluorinated coating is one way to repel water. At present, the use of shorter C-6 fluorinated coating is considered as environmentally safe and the US Army has evaluated commercially available C-6 fabrics (such as, "EverShield") in order to examine appropriate application to their military uniforms (Gibson 2005).

Water-repellent military uniforms which protect soldiers from getting wet are beneficial. Such uniforms can be beneficial for soldiers although the water-repellent fabrics have different properties from waterproof fabrics which exclude water under pressure such as heavy/driving rain or cross bodies of water. Water-repellent coatings could minimize soldier's contact with cold water and thus minimize the saturation of their clothing in general. The hypothermia of soldiers subject to cold and rain could be minimized through water repellent combat uniforms. Furthermore, water-repellent combat uniform may be somewhat helpful in protecting soldiers from chemical and biological (CB) contaminations. CB protective clothing relies on a fluorocarbon finished outer-shell fabric to minimize surface wetting by water and liquid chemicals. Such an outer-shell fabric offers as much as a 90% reduction in permeation of toxic chemicals through clothing (Truong & Pomerantz 2018). Also, omniphobic coated textiles pick up dirt about eight times less than untreated fabric (Truong & Pomerantz 2018).

There are a number of test factors to evaluate the water-repellant performance of textiles: contact angle, time of wetting, time to dry, the droplet weathering, liquid adsorption, drop roll off, or vertical wicking resistance. However, these test factors are typically conducted on plain fabrics and do not take into account factor such as clothing design, closures, openings, layering, or seams. These latter test factors are especially relevant for during walking or running, and for thermal comfort (such as, thermal resistance, evaporative resistance, and air permeability) the factors could be tested. To address this issue a rainfall tower system with the ability to evaluate protective function of clothing ensemble from rainfall is vital. BS EN 14360 (2004) specifies a test method for determining the rain-protective function of clothing using a static manikin under a rainfall tower. An adult-sized manikin wearing test clothing is exposed to artificial rain for a specific period in the rainfall tower. There is very little research using a manikin and the test method of BS EN 14360 (2004). The rainfall tower system is a building comprising a circular tub at least 5 m above the floor, which supplies water from an inflow pipe and allowed controlling the density of rainfall.

In this context, we evaluated the water-repellent performance of newly-developed combat uniforms using both a static manikin and human subjects in the rainfall tower system. The hypotheses were as follows: (1) wetting time would take longer for the water-repellent combat uniforms than for the current combat uniform in both static and walking conditions, (2) the upper body inside combat shirts would become wet quicker than the lower body regions inside combat pants in both static and walking conditions, (3) water repellency of hydrophobic coating would not reduce through washes, and (4) clothing microclimate humidity would continue to increase even during recovery after the rain-stopped in human wear trials.

Methods

Physical characteristics of experimental combat uniforms

Two kinds of water-repellent (WR) combat uniforms, which were newly-developed for the present study, were compared to the current Korean combat uniform. Original textiles of the combat uniform (Polyester 70% and Rayon 30%) were coated using C-6 fluorinated water repellents (Company M) and perfluorinated compounds free (PFC-free) water repellents (Company T) but with the different techniques of two different companies. Detailed technologies were not disclosed to the public because the technologies were company confidential. The physical characteristics of the three combat uniforms of the present study are presented in Table 1. All combat uniforms consisted of a long-sleeved shirt and a long-legged pants. The total weights of the clothing ensembles (shirt and pants) were 959 g, 957 g and 989 g for the Control, WR_M, and WR_T combat uniform, respectively. The static manikin test and human wear trials evaluated the three types of combat uniforms.

Test using artificial rainfall and a static manikin

A rainfall tower system was installed with an artificial rainfall system that caused rain to fall from a height of 10 m above the ground (Fig. 1). The rain was set to fall from an area of 2 × 1 m (width × longitudinal) and with 1000 water droplets per 1 m^2 following BS EN 14360 (2004). The three types of combat uniforms in Table 1 were evaluated under the normal rain condition (150 ± 50 $mm \cdot h^{-1}$) and heavy rain condition (300 ± 50 $mm \cdot h^{-1}$). Combat uniforms which had undergone 10 washes were compared with each condition (3 types of combat uniforms × with/without washes × normal/heavy rain = 3 × 2 × 2 = a total of 12 experimental conditions). In general, a washing fastness test is conducted after 10 and 20 washes (Choi et al. 2008), and the test in the present study was conducted

Table 1 Physical characteristics of the current and two water-repellent combat textiles

Property of textiles	Test method	Untreated textiles (Control)	Water-repellent (WR_M)	Water-repellent (WR_T)
Water-repellent coating material	–	Untreated	C-6	PFC-free
Fabric weight ($g \cdot cm^{-2}$)		0.018	0.017	0.019
Fabric thickness (mm)		0.346	0.398	0.360
Tensile strength _ warp/weft (N)	KS K 0520	> 540/> 450	920/590	660/510
Tearing strength _ warp/weft (N)		> 30/> 30	49/34	110/110
Stretch and recovery rate (%)	KS K 0352	> 65	87.5	86.1
Air permeability (cfm)	KS K 0570	30.2	27.7	31.2
Water repellency before washing (level)	KS K 0590	0	5	5
Water repellency after 30-time washing (level)	KS K ISO 4920	0	3	4
Resistance to water penetration of seam (cmH_2O)	KS K ISO 811	Wetted	13.7	14.4
Water vapor permeability-calcium test ($g \cdot m^{-2} \cdot 24\ h^{-1}$)	KS K 0594	9432	7576	7985
Water vapor permeability ($g \cdot m^{-2} \cdot 24\ h^{-1}$)	KS K 0594	Wetted	30,973	27,388
Water vapor resistance ($m^2 \cdot Pa \cdot W^{-1}$)	ISO 11092	2.40	3.59	3.07
Moisture absorption/quick drying rate (OMMC, level)	AATCC 195	3	1	1

Three to five measurements were averaged

Fig. 1 Rainfall tower system (left), rain nozzles of the top (middle) and the static manikin with combat uniform (right)

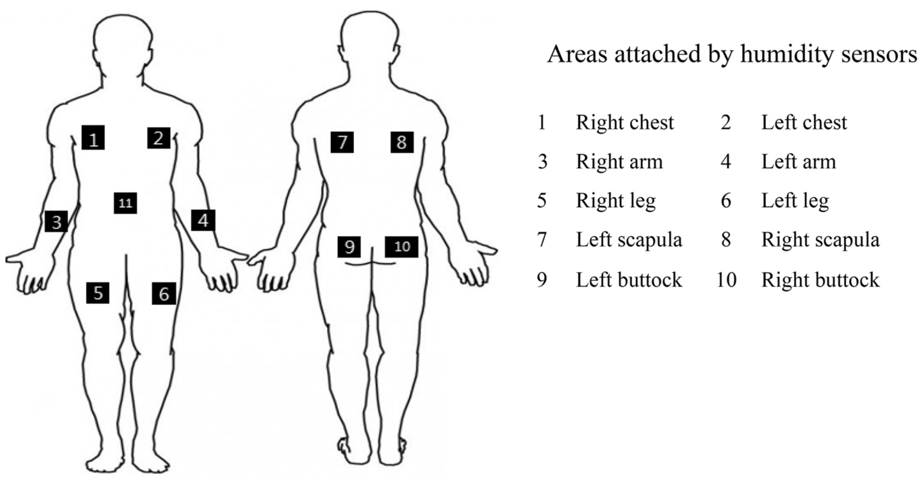

Fig. 2 Eleven body regions where humidity sensors were attached

after 10 washes based on the number of summer combat uniforms provided for each soldier and training schedules in routine. The static manikin was a replica of an adult male (a height of 182 cm, consisting of the head, torso, buttocks, arms, hands, legs, feet, etc.). Cylindrical humidity sensors (HM 1599LF, TE connectivity company, Switzerland) were attached to the 11 body regions of the manikin surface to determine when rainwater penetrated the combat uniform (Fig. 2). This study evaluated the performance of water-repellent uniforms based on static manikin as well as human wear trials, and the identical measurement sites in the manikin and human wear trials were selected from the measurement locations presented in the BS EN 14360 (2004). The combat shirts and pants were positioned on the manikin without underwear, and plastic bags were used to cover the head and neck in order to avoid water entering through the neck opening. The size of all the test garments was identical. After 60 min of exposure to rainfall, we allowed the test garments to drain for 2 min, following BS EN 14360 (2004), and then removed the test garments carefully. The air temperature and humidity inside the rainfall tower was maintained at 25 °C and 65%RH. All data from the humidity sensors were continuously recorded every 1 s for 60 min.

Human wear trials in the rainfall tower system

Eight healthy male subjects (28.4 ± 5.42 y in age, 174 ± 5 cm in height, and 71.4 ± 8.6 kg in body weight) participated in the three experimental conditions of the three combat uniforms. Informed consent was obtained from all subjects. The experiment was approved by the institutional review board of Seoul National University (IRB # 2008/002-004). Three identical combat uniforms were selected for the static manikin test. Human subjects wore briefs, combat boots, a combat uniform shirt and trousers. The order of participation was counter-balanced to avoid any possible order effect.

The ambient air temperature and humidity inside the rainfall tower were maintained at 22.0 ± 0.5 °C and 86 ± 7%RH for the rainfall condition and at 22.9 ± 0.6 °C and 79 ± 4%RH for the rest condition (no rain period). The experimental protocol consisted of 10-min rest in a sitting position outside the rainfall tower followed by 30-min of walking at a speed of 4–5 km·h^{-1} on a stepper (IN MOTION-easybike, All trade international Ltd, China) with 70 beats per minute of a metronome, followed by a 20-min recovery in the same sitting position at the same location as the rest session (60-min protocol in a trial). Prior to donning the experimental clothing, clothing microclimate temperature and humidity sensors (TR-72U, T&D Corp., Japan) were attached to the four body parts (the chest, upper back, forearm and thigh) and clothing microclimate temperature and humidity were continuously recorded every 5 s. Clothing microclimate is defined as the temperature and humidity of air layer between clothing and body surface, which differs from the skin (surface) temperature or humidity.

Subjects evaluated themselves via questionnaire during the 20-min recovery session, just after 30-min of walking in order to evaluate the water-repellent properties under a rainfall condition. Subjects evaluated themselves in terms of tactile skin sensation, softness, wetting time, heaviness of wet clothes, humidity sensation, thermal sensation and thermal comfort on a seven-point categorical scale. In addition, an additional question on the wet areas and general performance of combat uniforms was provided. The total masses of the dry and wet clothing were measured just before starting and just after finishing each trial using a scale (Resolution 5 g, FM-917, CAS, Korea). The time process of measuring wetted clothing mass was accurately followed by the experimental protocol.

Data analysis and statistics

For both the static manikin test and the human wear trials, the wetting time was determined by the moment that microclimate humidity reached 90%RH, followed the recommendation of Cha et al. (2015). For the human wear trials, the values of the rest, walking, and recovery sessions were the averages of the 0–10, 10–40, and 40–60th minute periods, respectively, and those values were used as representative values for each phase. Repeated measures ANOVA and Wilcoxon tests were performed to evaluate any differences between the three conditions. Perceptual data from the subjective evaluation were analyzed with non-parametric statistical tests. The relationship between the clothing microclimate temperature and perceptual data was analyzed with the Spearman correlation. Statistical significance was set at $P < 0.05$.

Results

Static manikin test

Wetting time

There was a significant difference in the wetting time for the upper body among the three uniform conditions and WR_T showed longer time of wetting than that in Control condition. ($P < 0.001$, Table 2). WR_M was positioned between WR_T and Control. No statistical differences were found between no-wash and 10-time wash conditions. Regarding the normal and heavy rain conditions, on average, combat uniforms were wet earlier for the heavy rain than for the normal rain condition, but this difference was not statistically relevant (Table 2). No statistical difference between left and right body regions were found ($P = 0.102$). In the case of Control, all regions of the upper body were wet within 10 min, while WR_M and WR_T conditions showed around 10–15 min and 15–30 min for wetting, respectively. For the lower body parts, many cases of no wetting were found for WR_M and WR_T. In particular, no lower body regions were wet for WR_T during the normal rain (Table 2). Among the chest, upper back and forearm, it was difficult to discern what body region was became wet the fastest because of different tendencies of the normal/heavy, no wash/washes and 3 uniform conditions. Differences in wetting time between the right and left body regions were found (Table 2).

Clothing microclimate humidity

Among the 11 body regions, three were taken as representative for humidity over the 60 min time course (Fig. 3). The current combat uniform (Control) was wet in 10 min, whereas water-repellent combat uniforms, especially WR_T, were wet later or not wet even after 60 min. For the heavy rain condition, lower body parts even covered by water-repellent uniforms were wet in 60 min (Fig. 3). Similar time courses in the clothing microclimate humidity for the 10-time wash conditions were observed.

Human wear trial

Wetting time

The wetting time was quicker for the Control than for WR_T but no significant difference was found among the three uniforms (Fig. 4). For Control and WR_M, time of wetting did not differ for the four regions but upper back and forearm were different for WR_T ($P < 0.05$). All three combat uniforms tended to be wet in the upper back region the quickest, while the forearm part tended to be wet the latest (Fig. 4).

Absorbed water mass after rainfall test

Changes in clothing weight between before and after the rainfall test were 729 ± 21, 256 ± 36 and 137 ± 25 g per trial for Control, WR_M, and WR_T, respectively ($P < 0.001$) (Fig. 5).

Clothing microclimate humidity and temperature

The difference in the microclimate humidity of the three combat uniforms at each period was not significant (Fig. 6), but significant differences according to body regions were

Table 2 Wetting time on the 11 body regions of the static manikin at 150 and 300 mm·h^{-1}

Unit: min	No washes						10-time washes						P^r	P^w	P^u
	Normal rain			Heavy rain			Normal rain			Heavy rain					
	Control[a]	WR_M[b]	WR_T[c]	Control	WR_M	WR_T	Control	WR_M	WR_T	Control	WR_M	WR_T			
Chest (R)*	2	9	12	5	9	4	4	9	35	3	7	5	0.229	0.498	0.067
Chest (L)	9	31	40	11	20	13	6	29	22	8	11	8	0.082	0.317	
Upper back (R)	6	8	31	3	3	4	9	22	32	6	25	14	0.174	0.174	0.015
Upper back (L)	9	8	13	8	9	17	6	11	36	8	10	11	0.499	0.544	
Forearm R)	2	3	7	1	2	30	4	3	25	5	2	40	0.463	0.489	<0.001
Forearm (L)	6	7	32	15	19	26	5	7	28	5	4	5	0.776	0.166	
Mean (SD): upper body	5.7 (3.1)	11.0 (10.0)	22.5 (13.5)	7.2 (5.2)	10.3 (7.7)	15.7 (10.9)	5.7 (1.9)	13.5 (9.9)	29.7 (5.6)	5.8 (1.9)	9.8 (8.2)	13.8 (13.3)	0.338	0.828	<0.001
Abdomen	4	57	N.S.	5	31	N.S.	6	3	N.S.	12	28	N.S.			
Thigh (R)	5	N.S.	N.S.	13	31	42	14	16	N.S.	8	N.S.	N.S.			
Thigh (L)	6	N.S.	N.S.	10	N.S.	N.S.	42	N.S.	N.S.	7	21	10			
Buttock (R)	30	N.S.	N.S.	5	N.S.	N.S.	25	N.S.	N.S.	26	11	N.S.			
Buttock (L)	N.S.	N.S.	N.S.	21	33	N.S.	38	N.S.	N.S.	50	N.S.	N.S.			

[a,b] and [c] represent Control, water-repellent M, and water-repellent T, respectively

[r,w] and [u] mean significant differences according to 2 rains, 2 washes and 3 uniforms, respectively

*(R) and (L) represent (right) and (left)

N.S. means cases which did not reach 90%RH of humidity until the end of the 60-min rainfall exposure

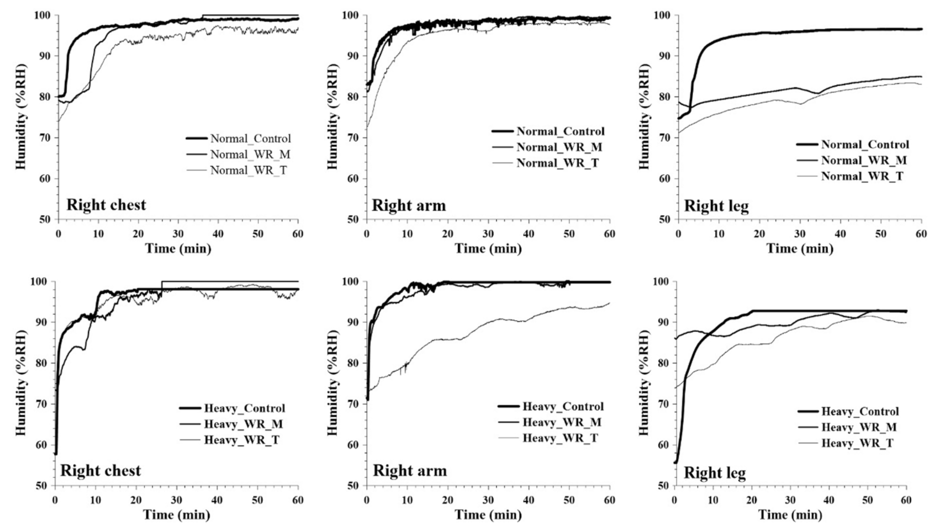

Fig. 3 Time courses of microclimate humidity when wearing combat uniforms with no washes

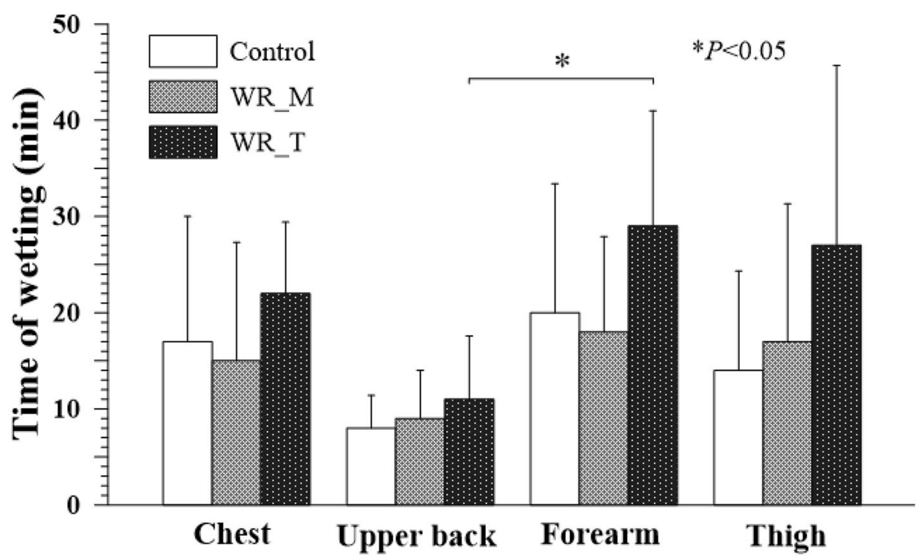

Fig. 4 Time of wetting on four body regions while walking at 150 mm h^{-1} rainfall

found. WR_T showed a significant difference between the four body regions ($P < 0.05$), and the difference was more notable during walking period. For Control, a body regional difference was found only in the difference between the forearm and upper back.

Clothing microclimate temperature was significantly different for the three uniforms during walking and recovery in the thigh region only (Fig. 7, $P < 0.05$). The microclimate temperature in the thigh region was the highest for WR_T and the lowest for Control (Fig. 7; 27.9 ± 1.1, 28.6 ± 0.9 and 30.2 ± 1.3 °C for Control, WR_M, and WR_T, respectively). However, the upper back showed 26.4 ± 1.3, 26.0 ± 2.3, and 26.3 ± 2.7 °C during walking without any differences between the three combat uniforms. When comparing

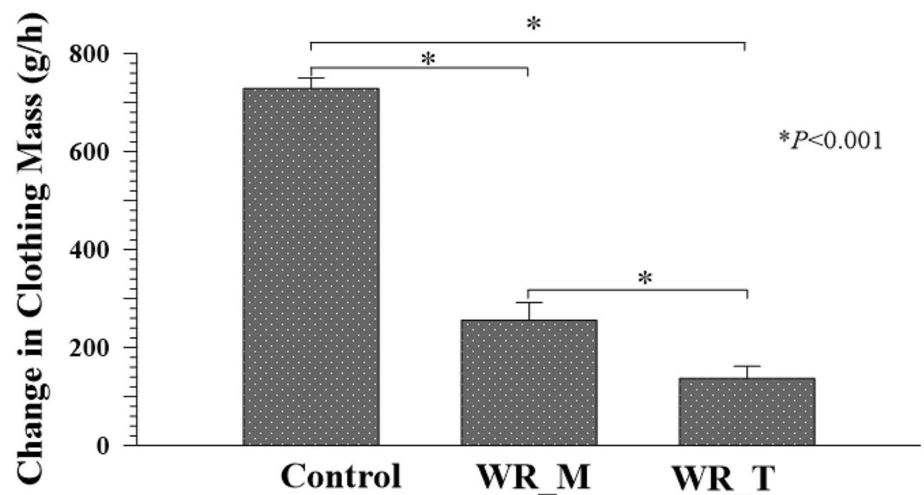

Fig. 5 Changes in clothing weight after the rainfall test. A 60-min trial consisted of 10-min rest followed by 30-min rainfall and 20 min recovery

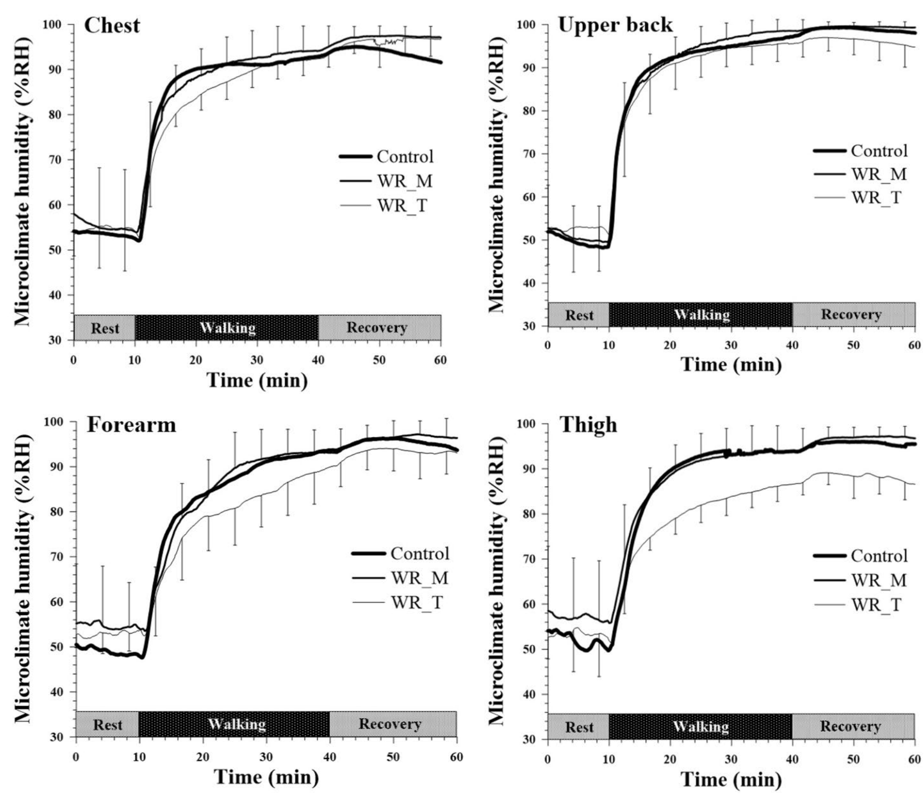

Fig. 6 Time courses of clothing microclimate humidity on the four body regions during rest, walking under 150 mm rainfall and recovery

the four body regions, the upper back microclimate temperature was lower than the chest microclimate temperature ($P < 0.05$) and a significant difference was found

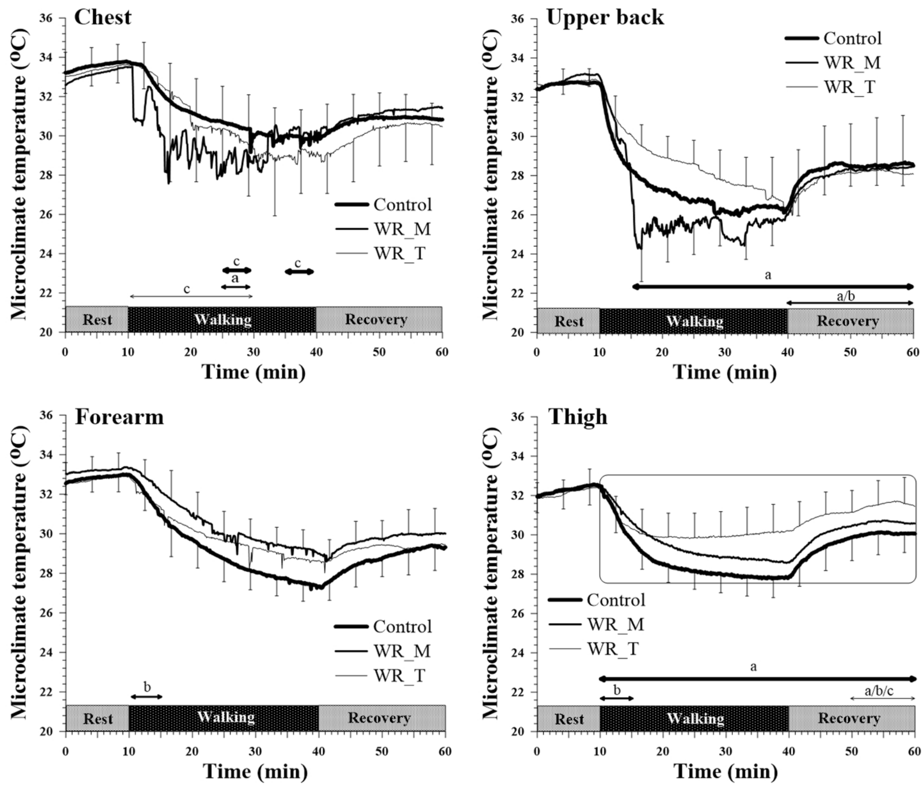

Fig. 7 Time courses of clothing microclimate temperature on the four body regions during rest, walking under 150 mm rainfall and recovery.

between the three combat uniform conditions. It is worth mentioning that microclimate temperature was ~ 6 °C lower by on average while walking than at rest.

A round rectangle shows that WR_T is significantly different from Control and WR_M ($P < 0.05$); Arrows indicate significant correlations between subjective evaluation and drop in clothing microclimate temperature; Different thicknesses of the arrows indicate the same as in the legend; a, b, and c indicate the significant correlation between temperature drop and thermal sensation, humidity sensation, or thermal comfort, respectively.

We found that there were significant relationships between subjective evaluation (such as thermal sensation, humidity sensation or thermal comfort) and drop in microclimate temperature (Fig. 7). In the case of chest, thermal sensation of WR_M ($\rho = 0.826$, $P < 0.05$) and thermal comfort of Control ($\rho = 0.726$, $P < 0.05$) and WR_T ($\rho = 0.774$–0.898, $P < 0.05$) were correlated with the clothing microclimate temperature. In the case of the upper back, thermal sensation of Control ($\rho = -0.769$ to -0.913, $P < 0.05$), thermal sensation ($\rho = -0.840$, $P < 0.01$) and humidity sensation ($\rho = 0.840$, $P < 0.01$) of WR_M showed correlations with the drop in the clothing microclimate temperature. In the case of forearm ($\rho = 0.756$, $P < 0.05$) and thigh ($\rho = -0.840$ to -0.924 for thermal sensation of Control, $\rho = -0.746$ to -0.869 for thermal sensation of WR_T, $\rho = 0.825$ for humid sensation of WR_M, $\rho = -0.750$ to -0.805 for humid sensation of WR_T, $\rho = -0.794$ to -0.895 for thermal comfort of WR_T, $P < 0.05$), similar relationships as those in the chest or upper back were found.

Subjective evaluation

There were significant differences between the seven subjective evaluations for the three combat uniforms. Subjects experienced better tactile sensation, softer sensation, less feeling of wetness, less cold sensation, less heavier sensation, less humid sensation, less uncomfortable feeling for WR_T than Control or WR_M ($P < 0.05$), while WR_M was better only for tactile sensation and heaviness than Control ($P < 0.05$, Table 3). Of the upper body, the chest was the wettest for all the three combat uniforms conditions.

Discussion

This research is original in terms of evaluating the performance of the water-repellent-finished combat uniforms using both a static manikin and dynamic human subjects under a rainfall tower system. Various variables, such as wetting time, clothing mass change, clothing microclimate and subjective evaluation, have been used to verify the level of water-repellency of a clothing ensemble from various perspectives. Although the level of water repellency of the new fabric itself (both WR_M and WR_T) was evaluated as the identical level 5, through the various variables of the rainfall test, these

Table 3 Subjective evaluation of the three combat uniforms just after walking in rain

	Control	WR_M	WR_T	*P* value
Tactile sensation (1 very poor, 2 poor, 3 slightly poor, 4 neutral, 5 slightly good, 6 good, 7 very good)	2.3 (1.2)[a]	4.4 (0.9)[b]	5.5 (0.9)[c]	<0.001
Softness (1 very poor, 2 poor, 3 slightly poor, 4 neutral, 5 slightly good, 6 good, 7 very good)	3.0 (1.1)[a]	3.8 (1.4)[a]	5.6 (0.9)[b]	<0.05
Time of wetting (1 very quick, 2 quick, 3 slightly quick, 4 neutral, 5 slightly slow, 6 slow, 7 very slow)	2.3 (1.8)[a]	3.3 (1.2)[a]	6.0 (0.5)[b]	<0.05
Thermal sensation (1 hot, 2 warm, 3 slightly warm, 4 neutral, 5 slightly cool, 6 cool, 7 cold)	6.4 (0.7)[a]	5.8 (1.0)[a]	4.1 (0.8)[b]	<0.05
Heaviness (1 very heavy, 2heavy, 3 slightly heavy, 4 neutral, 5 slightly light, 6 light, 7 very light)	2.1 (1.1)[a]	3.8 (0.9)[b]	5.3 (0.9)[c]	<0.05
Humid sensation (1 very humid, 2 humid, 3 slightly humid, 4 neutral, 5 slightly dry, 6 dry, 7 very dry)	1.9 (1.0)[a]	2.8 (1.0)[a,b]	4.0 (1.2)[b]	<0.05
Thermal comfort (1 very uncomfortable, 2 uncomfortable, 3 a little uncomfortable, 4 neutral, 5 a little comfortable, 6 comfortable, 7 very comfortable)	2.1 (1.4)[a]	3.0 (0.8)[a]	5.1 (1.1)[b]	<0.05
The most wetted part _ shirts (number of response, frequency)	Back (6) and Chest (6)	Shoulder (6)	Chest (7)	
The most wetted part _ trousers (number of response, frequency)	Thigh (8)	Thigh (8)	Thigh (8)	
Other opinions	Uniforms were heavy, wet, cold, and unpleasant	Water came into the uniforms and flowed from the body	Water came into the uniforms, but the uniforms didn't get wet and light	

[a, b] and [c] mean significant differences among the three groups by Tukey's post hoc test

water-repellent uniforms were classified into sub-levels of water repellency (e.g., excellent or fair class). Of course, such classification should be carefully announced with further experiments and one can take the current discussion as a proposal stage for new criterion. The experimental factors that we tested are as follows: (1) level of rainfall (150 and 300 mm·h^{-1}), (2) no wash versus 10-time washed, and (3) standing versus walking position. The three factors are more discussed along with the various variables.

Experimental factor 1: Normal or heavy rain

BS EN 14360 (2004) specified the level of rainfall as 450 mm·h^{-1}, and Cha et al. (2015) tested garments under the rainfall of 450 mm·h^{-1} as well as 100 mm·h^{-1}. However, we lowered the value of 450 mm·h^{-1} to 300 mm·h^{-1} (heavy rain) along with 150 mm·h^{-1} (normal rain) because the 450 mm·h^{-1} is very rare in Korea. The two levels of rainfall were applied to the static manikin test. For the human wear trial, we chose to apply only the 150 mm·h^{-1} (normal rain) to avoid any possible health risks. Overall, the time of wetting was shorter for the heavy rain condition than for the normal rain condition, but the difference between the normal and heavy rain conditions was not significant and exceptional cases are found. Also, WR_M and WR_T were classified into two levels in terms of the wetting time during the normal rain condition. These results indicate that the normal rain condition is sufficient to test water-repellent combat uniforms.

Experimental factor 2: No wash versus 10-time washed

According to our textile tests, WR_M and WR_T were both evaluated as having level 5 of water repellency, but these combat textiles after 30-washes have been evaluated as level 3 (WR_M) and level 4 (WR_T)(Table 1). The level means that the higher the numbers 1, 2, 3, 4 and 5, the better the performance of water repellency. We compared the uniform ensembles which were new and had been washed 10 times. Ten-washes was determined to be equivalent to 3 months of military use, based on facts that two pairs of summer combat uniforms are provided to each soldier and they do the laundry their combat uniforms once in 3–5 days (interviewed but unpublished). Even though the 30-time washed textiles showed a difference between WR_M and WR_T, the 10-time washed uniform ensembles did not show any significant differences in the time of wetting between WR_T and WR_M, and neither had diminished water repellent properties. Truong et al. (2013) reported that after 20 washes, the wetting contact angle of water repellent textiles, was over 150° which is superhydrophobic. Therefore, we recommend testing water-repellent combat uniforms which have not yet been washed for rainfall tests in the rainfall tower system. And if the effect of aging on combat uniforms is to be tested, over 30-time washed uniforms should be compared with new, unwashed uniforms.

Experimental factor 3: Standing and walking position

There was a significant difference between the standing and walking positions in terms of wetted body regions and the wetting time. For the standing position, no area of the lower body became wet for WR_T even after 60-min rainfall, whereas the thighs for

WR_T was wet in 30 min during walking even though the WR_T became wet slower than those in the other two uniform conditions. These results indicate that both static and dynamic positions should be tested to estimate the wetting time and wetted body regions. Havenith and Heus (2004) suggested that water protective clothing should be tested while doing various tasks such as climbing over objects, crawling under objects, moving crates, as well as walking, so as to further test the design of the clothing (no gaps when bending over), the materials, its seams, etc., Such clothing should be tested under normal conditions and under conditions of pressure and stretch. Further studies on combat mobility protocols are required.

Variable 1: Wetting time

Wetting time may be a valid variable to evaluate the level of water repellency of clothing ensembles because we found significant differences among the three uniform conditions. For the standing upper body, under the 150 $mm \cdot h^{-1}$of rainfall condition, wetting in under 10 min can be regarded as a fail case, while over 20 min is an excellent level and between 10 and 20 min is a fair level. As stated, these criteria are potential, not definitive. With these potential criteria, WR_T can be classified as having excellent water repellency (level 1 or class (1) while WR_M had a fair level (level 2 or class 2) of water repellency. During walking or other activities, the standard time limits for fail, fair and excellent levels should be reconsidered in light of further studies that measure more body regions.

Variable 2: Body region of wetting

Because we measured a total of 11 body regions in the static manikin test and only four body regions for the human wear trials, we are not able to conclude what body region was became wet the fastest under rainfall. In the present protocol, however, it is possible to conclude whether the upper or lower body region became wetter quicker. For both static and dynamic positions, the upper body was wet quicker than the lower body. In addition, there was no cases of the lower body in WR_T when standing becoming wet from the normal rain condition. From our results, no area of the lower body can be classified as being excellent for 60-min rainfall. For further studies, our suggestions are as follows: (1) an upper body and a lower body values should be averaged from the right and left body regions, (2) an upper body and a lower body wetted value should be averaged from values that include major seam lined regions and openings, as well as the chest, abdomen, upper back, lower back, upper arm, and forearm (or buttocks, thighs, and calves) (Cha et al. (2015) reported that rain leakage around the major seams were found), and (3) in the present study, we did not use a water-absorptive underwear to map wetted regions for either the manikin or human subject trials, but water-absorptive underwear can be used under water-repellent combat uniforms to examine the wetted regions of the entire body surface. Furthermore, the Military of National Defense can develop a combat jacket with stronger water-repellency and combat pants with less water repellency based on the present finding.

Variable 3: Clothing mass changes after rainfall test

As expected, WR_M and WR_T showed increases in clothing weight after rainfall tests. Through textile tests, moisture absorption and quick drying rates of WR_M and WR_T were all evaluated as class 1 (not wetted), while Control textile was evaluated as class 3 (Table 1). In the human wear trials, however, total weight of clothing ensemble increased 729 g, 256 g and 137 g for Control, WR_M, and WR_T, respectively. These results indicate that water-repellency can be classified into sub-levels using changes in clothing mass, even though the textile test could not distinguish the level of water-repellency because WR_M and WR_T textiles did not get wet. Galbraith et al. (1962) compared the changes in weight of cotton suits with those of water-repellent cotton suits in a hot and humid environment without rain, and found that the water-repellent cotton suit had a lower weight gain than the untreated cotton suit. They interpreted that this as being due to more liquid moisture left on the skin when wearing water-repellent cotton suit, which could be a source of discomfort. Therefore, further studies are needed to evaluate the thermo-physiological influences of WR_T in hot and humid environments with no rainfall.

Variable 4: Clothing microclimate humidity and temperature

In general, clothing microclimate humidity during human physical activity is related to thermal comfort, and higher humidity can be regarded as being thermally uncomfortable. However, in the rainfall tower test, clothing microclimate humidity can be used as a variable to evaluate rain repellency. Based on Cha et al. (2015) and our discussion, 90%RH within the clothing microclimate was determined as the point at which a uniform becomes wet inside. In this regard, continuously monitoring microclimate humidity is very critical to determine the time of wetting and wetted body regions.

An unexpected finding of the present study was that clothing microclimate temperature went down over time while walking under rainfall. In general, when walking, clothing microclimate temperature may be initially lowered due to forced convection, but over time it goes up because of body heat from the muscle. Usually, we evaluate that wearers are thermally comfortable when the clothing microclimate temperature around the chest or the upper back is maintained at 31–34 °C (Kim 2005; Kwon & Choi 2013). As described in Fig. 7, however, microclimate temperatures dropped below 30 °C which is interpreted as being wet inside the clothing and was maintained close to the comfortable range for WR_T. That is, originally, we predicted that wearing water-repellent combat uniforms might cause a thermally uncomfortable microclimate inside the clothing because of the water-repellent finish. Gibson (2008) reported that the addition of a non-wicking finish to clothing fabric impaired thermal comfort in hot and humid environments. In the present study, however, the clothing microclimate of WR_T while walking for 30-min in rain was closer a thermally comfortable temperature and humidity than wearing an untreated combat uniform. Therefore, clothing microclimate can be a variable to evaluate both water repellency of uniforms and thermal comfort of wearer while walking in rain.

Variable 5: Subjective evaluation

Each human wear trial was conducted as a single blind trial, which means that subjects did not notice which uniform condition they were wearing. Even though this was a blind study, subjective evaluations of WR_T were significantly different for from the other two uniform conditions, and WR_M was also distinguished from the Control in a couple of questions. Subjects felt that WR_T had better tactile sensation, was softer, became wet less quickly, was less cold, less heavy, less humid, and less uncomfortable than Control or WR_M. In addition, WR_M was evaluated better in terms of tactile and heaviness sensation than Control. These results indicate that subjective evaluations can be applied to classify the water-repellency of clothing ensemble into two levels. As described in Fig. 7, thermal sensation, humidity sensation, and thermal comfort were significantly related to clothing microclimate temperature, which suggests that subjective perceptions could be an alternative measure of clothing microclimate.

Limitation and suggestions

We suggested various parameters to evaluate the performance of water-repellent finished clothing under rain fall conditions. A limitation of the present study is that wetted area using water-absorptive underwear, which was already reported in BS EN 14360 (2004) and Cha et al. (2015), was not evaluated. The wetted area is a qualitative variable to identify the whole distribution of saturation as the first step of inspection, while wetting time, microclimate, or change in clothing mass can be applied to classify the level of water-repellency in more quantitative manner. As addressed, however, the classification of three levels (e.g., fail, fair, and excellent) that was proposed in the present study should not be considered as a definite criterion. The present study proposed such classification based on the limited results and the further experiments are required to validate the criteria. Lastly, in order to more elaborate the experimental protocol, we suggest to attach microclimate sensors under major seams and opening sites as well as the 11 body regions.

Conclusions

Even though the levels of water repellency of both finished textiles were evaluated as level 5, the water-repellency of the clothing ensemble made of these textiles can be classified into sub-levels with a rainfall test under a rainfall tower system. In order to verify the validity of our results, we suggest testing a clothing ensemble which has not been washed using both a static manikin and human subjects under 150 $mm{\cdot}h^{-1}$ of rainfall. At the above setting, taking over 20-min for wetting and no wetted areas from the lower body in a standing position and a less than 200 g increase in clothing mass while walking can be classified as excellent water repellency (WR_T), which are distinguished from the fair level of water repellency (WR_M). When compared to an untreated combat uniform, subjective questions with seven categories can be effectively applied to distinguish the excellent level from the fair level of water repellency. For further studies on the wetting dynamics of more body regions with water-absorptive underwear should be conducted.

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Authors' contributions
JK performed the experiment with human subjects, analyzed the data, and drafted the manuscript. KK conceptualized the manikin test, performed the manikin tests and data collection. JJ conceptualized the manikin test, performed the manikin tests and corrected the manuscript. JY conceptualized the entire research and design, performed the data analyses and the critical revision of the article. All authors read and approved the final manuscript.

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

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