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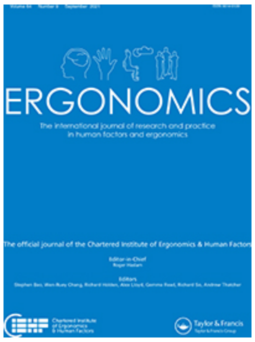

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The effects of chlorination, thickness, and moisture on glove donning efficiency

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ABSTRACT
Changing gloves more frequently is encouraged, more now than ever given the COVID-19 pandemic. When the donning process has moisture introduced, however, complications can arise, which consumes vital time. Most commonly, gloves undergo a chlorination treatment to reduce glove tack, allowing easier donning. To assess the effects of different chlorination strengths and glove thicknesses on donning, acrylonitrile butadiene gloves were manufactured at two different thicknesses (0.05 and 0.10 mm) with 4 different chlorination treatments: 0, 500, 1000 and 2000 ppm. Six participants were used to assess the time taken to don each of the glove sets with dry and wet hands (16 tests in total). Overall, the thicker gloves took longer to don, due to differences in the material stiffness hindering the donning process. The quickest performance from the chlorinated gloves was noted in the 1000 and 2000 ppm concentrations. Wet conditions also showed significant increases in the donning time.
Practitioners Summary: The study was conducted based on the gaps identified in previous literature reviews which revealed the requirement for a greater understanding of glove donning process. It was found a stronger chlorination was detrimental when the hands were wet, but better when dry. Thicker gloves were also found to be detrimental.

Abbreviations: PPE: personal protective equipment; NBR: acrylonitrile butadiene rubber; NRL: natural rubber latex; EN: European standards; s: seconds; Ts: tensile strength; Fb: force at break; T: thickness; Eb: elongation at break; HSD: honest significant difference; FTIR: Fourier transform infrared; covid-19: coronavirus disease 2019

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Donning; Chlorination; Medical Examination Gloves; Nitrile; Personal Protective Equipment

1. Introduction

Personal protective equipment (PPE) is arguably more important now than ever before, with the continuance of the COVID-19 pandemic. One of the most common types of PPE used are medical examination gloves, serving to cover the hands and protect them from contamination (Holland, Zaloga, and Friderici 2020). The ease of donning these gloves is paramount to the efficiency of clinical staff (Mylon, Lewis, Carré, and Martin 2014; Pavlovich et al. 1995; Edlich et al. 2003; Côté et al. 1998; Baloh et al. 2019). The ergonomics of glove donning, however, has received little attention. Previous studies have shown that wet hands require more force to don gloves, as the gloves stick to the hands more than when in a dry condition (Pavlovich et al. 1995; Edlich et al. 2003; Côté et al. 1998). Moisture can be incurred from the hand hygiene routines (hand washing after glove use) and/or through sweat on the hands (which can arise due to glove use). Inefficient drying, arising due to the fast-paced emergency situations often encountered by clinical staff, can lead to donning difficulties. These difficulties can consume valuable time and make the user either remove the gloves and continue the task without PPE, or swap them for a different type of glove, which wastes resources (Erasmus et al. 2010). In an attempt to circumvent these issues, the glove manufacturing industry has developed multiple ways to modify the inner surface of gloves, to enable easier donning (Ong 2001; Yip and Cacioli 2002; Preece, Lewis, and Carré 2020). The most common treatment applied to examination gloves is chlorination, in which the gloves are exposed to a chlorine gas or aqueous solution, which modifies the inner (donning) surface of the glove (Ong 2001; Truscott 2002; Roberts and Brackley 1992). This leads to a smoother surface, reducing tack from the manufacturing process, and ultimately reducing the friction and sticking when putting on the glove.

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However, multiple factors exist in the glove manufacturing processes which will have an effect on the end products. These factors can be anything from the raw materials used, formulation of glove film, manufacturing methodology, and the finishing of the gloves (Yip and Cacioli 2002; Akabane 2016).

Market trends have leaned towards the acrylonitrile butadiene rubber (NBR) material due to allergy concerns (Akabane 2016). Furthermore, the NBR material can be made thinner than the natural latex films (Yip and Cacioli 2002; Akabane 2016). Literature exists assessing medical examination gloves and how thickness differences can influence performance in carrying out tasks (Dianat, Haslegrave, and Stedmon 2012; Preece, Lewis, and Carré 2021; Mylon, Lewis, Carré, and Martin 2014). Although, little has been discussed in the literature regarding how the differences in thickness affects the performance of medical gloves in regard to donning. There is also very little in the literature which links the chlorination process to an easier physical donning process. However, there are studies that highlight the efficiency of chlorinating and use of polymer coating to reduce friction. For example, Roberts and Brackley have previously looked at the coating applied to NRL surgical gloves, looking at friction with skin and glass (Roberts and Brackley 1992; Roberts and Brackley 1996). The work suggests longer chlorination time induces less friction, and hydrogel performs better. A more recent study by Manhart et al. (2020) showed similar results when attempting to show a correlation between friction with animal models and human skin. However, this reduction in friction does not mean that the donning process is easier. Taking into account the material properties and polymer design, not just the surface modification, is an important factor in the donning process. Gloves may conform and stretch differently over the fingers, causing issues with adhesion. More recently Preece, Lewis, and Carré (2020) compared the time taken to don chlorinated and polymer coated natural rubber latex (NRL) and NBR examination gloves. The study found that polymer coated NRL gloves were quicker to don than the chlorinated across the 14 participants. However, donning time increased when NBR gloves were polymer coated, when compared to chlorinated. The authors also reported a difference in the material properties and the thicknesses between the glove materials. The study defined the donning process as being broken down into 4 key stages:

1. Picking up: time taken to remove the glove from the box/pick up the glove
2. Preparation: orientation of the glove and prepare for hand insertion
3. Hand insertion: time taken for the glove to cover the hand i.e. the time taken for the fingertips to reach the end of the gloves
4. Manipulation/material pulling: time taken to pull material to fit the hand after the glove is 'donned'.

Together, stages 2–4 were shown to be the most pertinent to donning gloves, as most contact is in these stages.

The aim of this study was to investigate the effects of thickness, chlorination strength and moisture on the donning process. The research into these glove differences allows for a deeper understanding of how material properties affect the complex donning process. This will enable glove users to better select materials which allow for easier donning and enable manufacturers to develop/market gloves which are aimed at facilitating a smoother donning process. An easier donning process will increase the compliance with hand hygiene regulations, reducing the risk of transmission of pathogens, such as COVID-19 (Baloh et al. 2019; Erasmus et al. 2010). In order to study the effects of thickness and chlorination, gloves need to be sourced which have the exact same manufacturing profiles, but only differ with surface treatment and thickness. In order to ascertain these, the glove films had to be manufactured specifically for this test. Due to the leaning of the market towards synthetic latex gloves, only the NBR glove material will be covered in this study (Akabane 2016).

2. Materials and methods

2.1. Glove manufacture

Acrylonitrile butadiene rubber (NBR) gloves were produced in-house at the Technical Centre of Synthomer Sdn Bhd, Kluang. The films were formed using Synthomer NBR 6348HS grade, via two methods that mimic the processes used for standard glove manufacture, but on a smaller scale. Methods differed only by the dwell time of the former dipped into both the coagulant and the compounded NBR latex, in order to create glove films of two different thickness. Synthomer 6348HS NBR was compounded, and the formers dipped into a mixture of calcium nitrate ($Ca(NO_3)_2$) and calcium carbonate ($CaCO_3$) coagulant for three seconds (s). The formers were then heat dried at 65 °C in an oven before being dipped into the compounded NBR for 3 s. Following this, the formers were placed into an oven to gel set at 100 °C for 1 min, before being dipped again for a further 3 s. This method created the thinner of the two films. The

Table 1. Glove samples used for donning.

Glove Sample	Chlorination strength (ppm)	Thickness (mm)
A	500	0.054 (±0.003)
B	1000	0.054 (±0.004)
C	2000	0.055 (±0.004)
D	0 (Control)	0.059 (±0.003)
E	500	0.098 (±0.003)
F	1000	0.100 (±0.005)
G	2000	0.104 (±0.004)
H	0 (Control)	0.103 (±0.006)

± indicates standard deviation.

thicker film was produced with the same method, however using double the dwell time (6 s). After the gelling process, the films were manually beaded by rolling the end of the glove down a few mm to create the cuff of the gloves. The films were then leached for 1 min in water at 100 °C, and then cured at 100–120 °C in an oven to create the finished dipped glove.

2.1.1. Chlorination

Chlorine solutions were made at concentrations of 500, 1000 and 2000 ppm (parts per million of chlorine), respectively based on the typical industrial practices (Ong 2001). Sodium hypochlorite (NaClO), hydrochloric acid (HCl), water (H_2O), and sodium thiosulphate ($Na_2S_2O_3$) were mixed to create the desired concentration in large plastic containers in which the formers could be immersed. The dipped gloves (still on the formers) were then placed into the aqueous chlorine solutions for 10 min. Some gloves from each thickness variant/set were skipped for the chlorination process to serve as a control for the testing. Following chlorination, the formers were then immersed in neutraliser solutions for 5 min before being leached, as before, at 60 °C with water. The gloves were then dried for 5 min at 100–120 °C before being removed from the former. Due to the availability of equipment, films were only made on medium-sized formers. To remove the unchlorinated (control) gloves from the formers, a light dusting of calcium carbonate ($CaCO_3$) powder was used to help with the release from the former. The gloves formulated were labelled from A-H and are shown in Table 1. Thickness was measured across the palm using a micrometer (Mitutoyo quick-mini, ± 0.01 mm).

2.2. Material testing

Materials were tested as per EN regulations, using a Tinius Olsen (TL-190) tensometer with a speed of 500 (±2) mm/min. The EN 455 standards lay out the requirements of testing for physical properties. The standards state that gloves should be cut to yield a 3 mm wide strip, and to be tested at 21 °C (±2 °C) with a humidity at 50% (±5%) (British Standards International 2015). The material was press cut around the palm area to yield a 9 cm long section, which has a 3 mm wide testing section as set out in the EN guidelines. The thickness along the 3 mm wide strip was measured three times and averaged using a micrometer (Mitutoyo, C11XBS). This was then loaded on the tensile tester and tested for the force at break, elongation at break, and tensile strength with an initial measurement length of 25 mm. Testing was carried out in a temperature and humidity-controlled room within the EN standards specification range discussed above. Each test was repeated 12 times to obtain an average.

2.3. Participants

Four males and two females participated in this study ($n = 6$). Ages ranged between 22 and 28 years old. Participants did not have any known skin issues or any allergies that could be triggered by the use of these gloves. Participants used gloves on average 1–2 times per week and had a perceived 'best-fit' for medium sized gloves (i.e. they do not usually wear any other sized glove than medium). Prior to being recruited into the tests, the participants were asked to don a pair of the gloves to ensure fit. The length of the participants hands and palm circumference were compared to the Health and Safety Executive chart (HSE, 2010), as in previous studies (Preece, Lewis, and Carré 2020). The comparison showed that two participants were recommended to wear large, while three were recommended medium, and one was recommended small. There did not appear to be any visual issues with fit once the gloves were donned. Each participant stated that the glove fitted them as they expected, and the fit was not significantly different from what they would normally expect. This discrepancy between perceived best-fit and the recommended size has been noted previously (Preece, Lewis, and Carré 2020).

2.4. Donning methodology

Participants were instructed to wash and dry their hands with soap and water 15 min prior to the experiment being conducted to clean contaminants from the hands. Participants then sat for 15 min to acclimatise to the room. The study was set-up as in Figure 1. One pair of gloves was placed on the table, out of any packaging, in front of the participants. The cameras were then switched on and the participants were instructed to don the gloves in front of them, in the same manner they would normally don gloves. This was repeated 8 times (once for each glove set (A-H)). To assess the effects of moisture on the hands, the participants were asked to wash their hands with soap and water. In order to dry their hands, participants were asked to pat them dry with paper towels, rather than wipe completely dry. The amount of moisture present was measured using a Moist Sense device, discussed in section 2.4.1. The test was then repeated as before. Each time the gloves were changed for the wet assessment, participants were asked to wash and dry their hands as before. The order of the gloves was changed for each participant in a forced randomised fashion. For logistical reasons (e.g. time for skin to dry out fully), the participants always donned the gloves in the dry hand condition before the test was conducted in the wet condition. Tests were carried out in the Human Interaction Group laboratory at the University of Sheffield with a room temperature range of 21–24 °C and 50–56% humidity. This project received ethical approval by the Department of Mechanical Engineering Ethics Committee at The University of Sheffield (W. M. Association 2013). All three cameras were analysed to assess the time taken to don the gloves at each stage of the donning process discovered in a previous study and discussed in the introduction (Preece, Lewis, and Carré 2020).

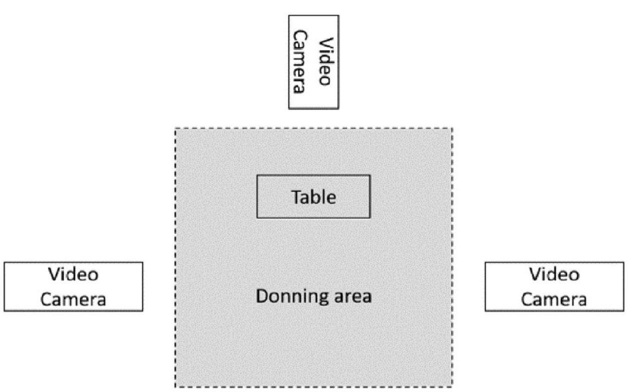

Figure 1. Experimental set-up for donning procedure. Donning area, where the hands are in view of the camera, is shown in grey. The participant was standing in the donning area with hands in front of the table.

2.4.1. Moisture measurements

Moisture in the hand was measured using a Moist Sense device, as shown in Figure 2 (Moritex 2015). This was conducted for each test in each condition. The scale on the device is given in arbitrary units (A.U.). A reading of lower than 40 A.U. indicates dry skin, between 40 A.U. and 70 A.U. indicates a 'normal' reading, and above 70 A.U. indicates moist skin. Readings were taken before each glove pair was donned to ensure skin was in the 40–70 A.U. range for the 'dry condition' and above 70 A.U. for the moist condition. Readings were taken in three regions: fingers, palm and back of the hands. One reading at each of the fingers/thumb tip. Two readings at the top of the palm, one in the centre and two at the base of the palm. On the back of the hands, two measurements were taken below the knuckle, one in the centre and two at the base of the back of the hand. Tests were conducted immediately after taking the moisture measurements. A diagram of the measurement locations is shown in Figure 3.

2.5. Statistical analysis

The Shaprio–Wilks test for normality was used to assess the time taken to don the gloves for normal distribution. Where the data was found to be normally distributed, data was analysed using one-way analysis of variance (ANOVA). Tukey Honestly Significant Difference (HSD) was used as a post-hoc test to assess for differences between gloves of the same thickness and moisture composition (Bondell and Reich 2009). Where data was found to be non-parametric, significance was tested for via the Kruskal-Wallis method, before conducting a post-hoc Dunn's Multiple Comparison Test, where required (Dinno 2015). Statistical differences between the two glove thicknesses for each strength of chlorination was assessed using a paired *t*-test (where data was parametric) or Wilcoxon test (where data was non-parametric)

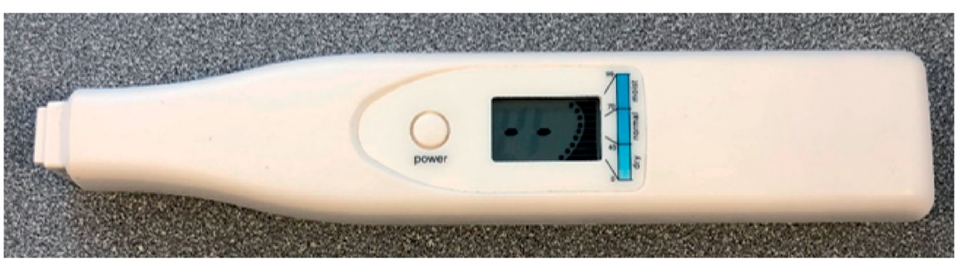

Figure 2. Moist sense device used for measuring skin moisture.

Figure 3. Diagram of hands where moisture measurements were taken.

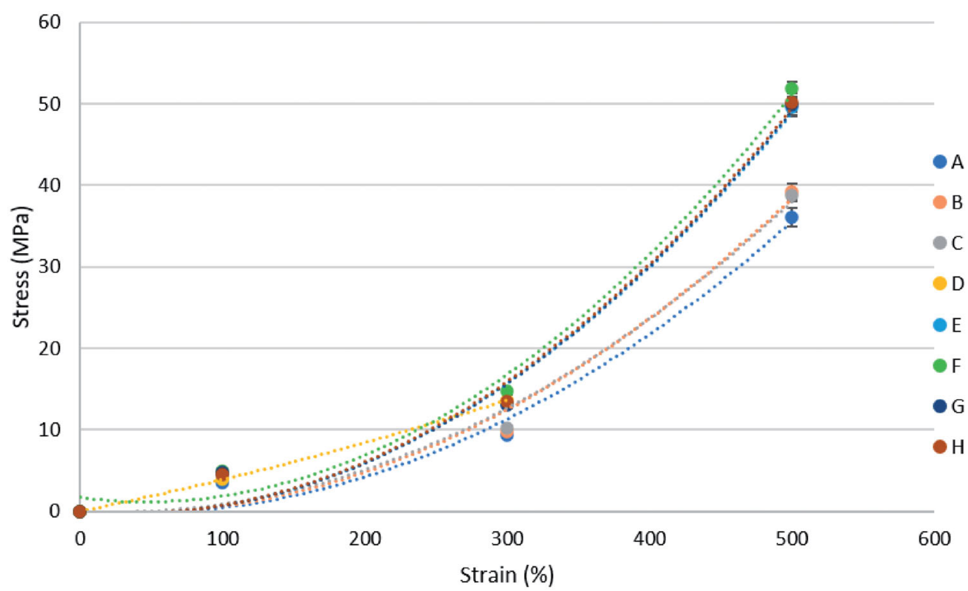

Figure 4. Stress-strain curve of each in-house formed glove. Error bars indicate standard deviation.

(Wilcoxon 1945). Statistical significance is set at $\alpha = 0.05$, thus significant differences are shown at $p < 0.05$. For the graphs showing collated participant donning data, error bars show the calculated standard error, to indicate the accuracy of the mean value calculated.

The Pearson correlation coefficient (r) was calculated to assess correlations between donning time and the physical parameters. The r ranges from 1 to -1. A value of 0 shows no association between the two variables (Schober, Boer, and Schwarte 2018; Mukaka 2012). The correlation value can then be tested for statistical significance, which indicates how significant the correlation is (Gogtay and Thatte 2017).

3. Results

3.1. Physical parameters

The stress-strain curves obtained from the tensile testing are shown in Figure 4. The thicker material chlorinated at 1000 ppm (F) shows the highest stress at 500% strain, with the thin 500 ppm (A) sample showing the lowest stress at 500% strain. Only one material ruptured before 500%, which was the thinner control (D). This rupture was not observed in the control glove in the thicker materials. The modulus of all thicker gloves are in the same region; however, sample F does have a slightly higher modulus to the other thicker gloves.

Table 2. Results of physical testing of the glove materials.

Sample ID	T (mm)	Fb (N)	Ts (MPa)	Eb (%)	Stiffness (N/mm)
A	0.054 (±0.003)	6.50 (±0.49)	39.90 (±2.88)	506.58 (±25.69)	0.022 (±0.003)
B	0.054 (±0.004)	6.93 (±0.55)	42.79 (±3.37)	511.00 (±16.73)	0.030 (±0.006)
C	0.055 (±0.004)	6.71 (±0.80)	40.96 (±3.40)	489.00 (±23.63)	0.030 (±0.009)
D	0.059 (±0.003)	6.93 (±0.90)	38.97 (±4.93)	436.00 (±39.06)	0.026 (±0.003)
E	0.098 (±0.003)	16.50 (±1.12)	56.00 (±3.64)	528.50 (±10.88)	0.059 (±0.003)
F	0.100 (±0.005)	16.30 (±1.14)	54.55 (±3.45	502.83 (±16.35)	0.059 (±0.005)
G	0.104 (±0.004)	17.64 (±2.23)	56.78 (±7.68)	526.75 (14.67)	0.059 (±0.005)
H	0.103 (±0.006)	17.23 (±1.45)	55.98 (±4.65)	523.00 (13.82)	0.055 (±0.004)

± indicates standard deviation.

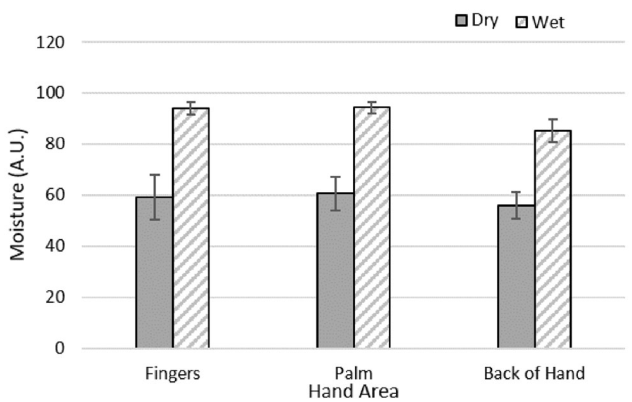

Figure 5. Average skin moisture on the hands in dry and wet conditions. Error bars indicate standard deviation.

The results obtained from the mechanical testing of the gloves are shown in Table 2. The results show the 8 glove sets with two distinct thicknesses (T). The material properties are shown to have greater break force (Fb), tensile strength (Ts), and elongation at break (Eb) when the gloves are thicker. The stiffness of each of the materials has also been calculated using the stress at 100% using the following formula:

$$Stiffness = \frac{stress \times Fb \times T}{Inital\ sample\ length}$$

Stiffness is found to be similar in the thicker materials which are chlorinated (0.059 N/mm), however more variation is noted in the thinner materials. Sample A has a lower stiffness at 0.022 (±0.003) N/mm, whereas B and C have greater stiffness at 0.030 N/mm. Sample A also shows a lower stiffness than the non-chlorinated control (sample D), with a stiffness of 0.026 (±0.003) N/mm.

3.2. Skin moisture

An average of the moisture results for all participants is shown in Figure 5. In the dry conditions, the average moisture between the participants is shown to be 59.23 A.U. (±8.85) for the fingers, 60.55 A.U. (±6.70) for the palm area, and 56.07 A.U. (±5.24) for the back of the hand. After the hands were made wet from washing, the average moisture between the participants is shown to be higher at 93.95 A.U. (±2.57) for the fingers, 94.19 A.U. (±2.39) for the palm area, and 85.15 A.U. (±4.49) for the back of the hand.

Table 3. Total average time taken to don one glove with pick up time removed.

Glove	Time (S)	
	Dry	Wet
A	13.39 (±2.75)	20.88 (±6.41)
B	11.24 (±2.26)	16.67 (±6.21)
C	10.31 (±2.98)	21.48 (±6.11)
D	12.64 (±1.49)	16.46 (±3.51)
E	16.06 (±6.42)	25.82 (±5.42)
F	16.12 (±4.56)	21.89 (±4.82)
G	11.40 (±3.60)	24.13 (±5.76)
H	12.46 (±3.98)	18.14 (±3.98)

± indicates standard deviation.

3.3. Donning performance

Analysis has only been conducted on the three key stages of the process where the glove is being used (preparation, hand insertion, and manipulation), as per the previous study (Preece, Lewis, and Carré 2020). Table 3 shows the average time taken to don one glove across the 6 participants, whilst Figure 6 shows the total time composed of the three individual stages of donning. There was an increase in the average time taken to don gloves when the hands had more moisture present. Glove C was the quickest to don when dry, taking 10.31 (±2.98) s on average, whilst glove F took the longest, taking 16.12 (±4.56) s on average. When the hands were wet, both controls were the quickest to don, with glove D taking 16.46 (±3.51) s, and glove H taking 18.14 (±3.98) s. However, when chlorinated, the 1000 ppm gloves in both thicknesses were quicker to don (B; 16.67 (±6.21), F; 21.89 (±4.82) s). Gloves C and G (2000 ppm) showed to have the greatest difference between the dry and wet conditions, increasing by 11.17 and 12.73 s, respectively when moisture was present. ANOVA tests across the glove thicknesses show no statistically significant differences throughout the total time for the thin gloves ($p < 0.05$). However, significant differences are present

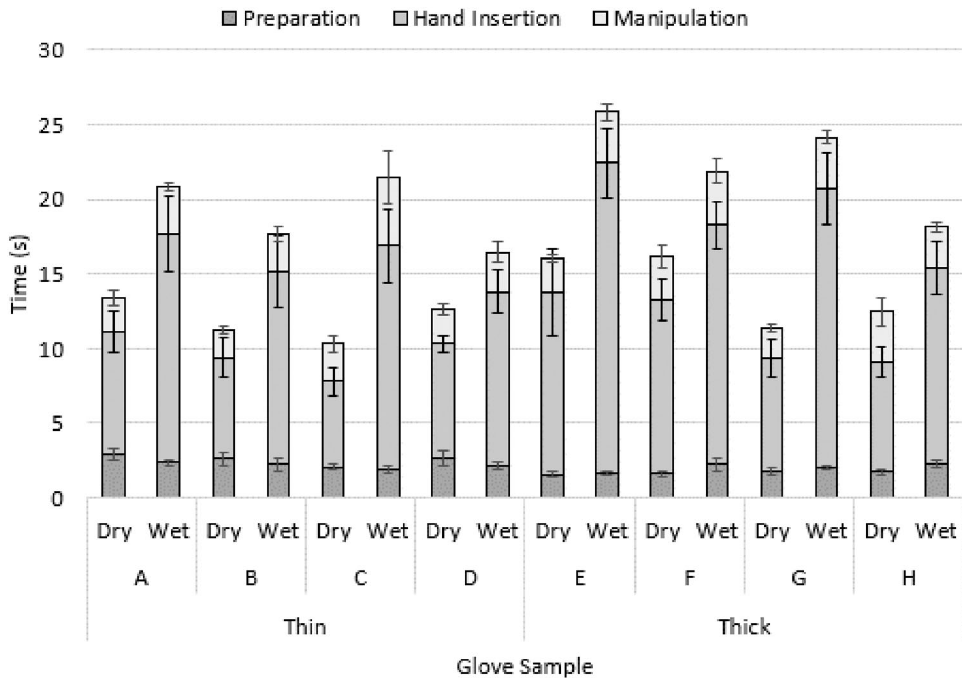

Figure 6. Average time taken for each of the three donning stages to be completed for one glove. Error bars indicate standard error.

Table 4. One-way ANOVA on the donning time of a single glove in each condition.

	p-Value	
Condition	Thin	Thick
Dry	0.075	0.197
Wet	0.087	0.048*

*Indicates statistical significance ($p < 0.05$).

Table 5. Tukey's (HSD) on the thick gloves in the wet condition.

	p-value		
Glove sample	E	F	G
F	0.500	–	–
G	0.900	0.835	–
H	0.040*	0.534	0.153

*Indicates statistical significance ($p < 0.05$).

across the thick gloves in the wet condition ($p = 0.048$) (Table 4). Table 5 shows the results following a post-hoc Tukey HSD test on the thick gloves in the wet condition. Significance is noted only between samples E (25.82 (±5.42) s) and H (18.14 (±3.98) s) ($p = 0.04$).

Further exploratory analyses were performed on each stage of the donning process. As most of the datasets being compared were non-parametric, Kruskal-Wallis tests for non-parametric data were used to compare the thin and thick gloves in both the dry and wet conditions (Table 6). No statistically significant differences were present between the gloves in the preparation or the manipulation stage of the donning process ($p > 0.05$). However, significant differences were found between the thick gloves in the hand insertion stage for the wet condition ($p = 0.019$). The hand insertion stage was then subjected to a post-hoc Dunn's test for non-parametric data, which shows statistically significant differences between gloves E and H ($p = 0.002$, Table 7).

Table 6. *p*-Values of Kruskal–Wallis test on thin and thick gloves in dry and wet conditions from the hand insertion stage of donning.

	p-Value	
Condition	Thin	Thick
Dry	0.222	0.133
Wet	0.353	0.019*

*Indicates statistical significance ($p < 0.05$).

Table 7. *p*-Values of post-hoc Dunn's test on thick gloves in the wet condition from the hand insertion stage of donning.

	p-Value		
Glove sample	E	F	G
F	0.066	–	–
G	0.268	0.466	–
H	0.002*	0.221	0.051

*Indicates statistical significance ($p < 0.05$).

3.3.1. Thickness

Paired *t*-tests show no statistically significant differences ($p > 0.05$) between the thin and thick gloves at each chlorination, with the exception of the 1000 ppm

Table 8. *T*-test results comparing thin and thick gloves in dry and wet conditions.

Glove samples	*p*-Value Dry	Wet
A–E	0.115	0.630
B–F	0.008*	0.828
C–G	0.503	0.252
D–H	0.897	0.350

*Indicates statistical significance ($p < 0.05$).

Table 9. *p*-Values obtained from paired *t*-tests between gloves in dry and wet conditions at each stage of the donning process.

	p-Value			
Glove sample	Total time	Preparation	Hand insertion	Manipulation
A	0.001*	0.122$^{\Delta}$	0.002*	0.158$^{\Delta}$
B	0.008*	0.552	0.002*	0.145
C	0.013*	0.580	0.001*	0.159$^{\Delta}$
D	0.016*$^{\Delta}$	0.255	0.005*$^{\Delta}$	0.502$^{\Delta}$
E	0.006*	0.588	0.005*	0.125
F	0.075	0.177$^{\Delta}$	0.005*$^{\Delta}$	0.464$^{\Delta}$
G	0.001*	0.521	0.003*	0.107$^{\Delta}$
H	0.010*	0.828	0.005*	0.381$^{\Delta}$

*Indicates statistical significance ($p < 0.05$). $^{\Delta}$Indicates Wilcoxon Signed Rank Tests carried out due to either one or both datasets being non-parametric.

chlorination when gloves are donned in the dry condition ($p = 0.008$) (Table 8). The smallest difference is observed with the control gloves (D, H), which differ by 0.14 s on average between thickness in the dry condition. The largest difference observed is with the 500 ppm (A, E) gloves in the wet condition, which differ by 4.94 s, on average.

3.3.2. Moisture measurements

Paired *t*-tests were conducted to assess differences in moisture. Significant differences ($p < 0.05$) were found between total donning times in the dry and wet hand conditions for each of the gloves, with the exception of glove F ($p > 0.05$, Table 9). In the preparation and manipulation stages, no statistically significant differences were found for any of the samples ($p > 0.05$). In the hand-insertion stage, however, statistically significant differences were found for all glove samples ($p < 0.05$).

3.4. Correlation of stiffness

Table 10 shows the Pearson correlation coefficients between the stiffness of each glove, and the time taken for each stage of the donning process as well as the total time take to don the gloves. Correlations are shown more frequently in the dry condition than the wet condition. The wet condition shows no correlation

Table 10. Correlation of stiffness at 100% strain with total donning time and each of the three stages of the donning process.

	Stiffness at 100% strain							
	Total		Preparation		Hand insertion		Manipulation	
	r	*p*	*r*	*p*	*r*	*p*	*r*	*p*
Dry	0.420[a]	0.300	−0.908[c]	0.002*	0.510[b]	0.197	0.419[a]	0.301
Wet	0.503[b]	0.204	0.221	0.599	0.535[b]	0.172	0.069	0.871

[a]Indicates a weak correlation. [b]Indicates a moderate correlation. [c]Indicates a strong correlation. *Indicates statistical significance.

in the preparation or manipulation stages of the donning process. Furthermore, a statistically significant correlation is present between the preparation stage in the dry condition and the material stiffness ($r = -0.908$; $p = 0.002$). As this correlation is negative, this implies that the stiffer the material, the easier it is to prepare/open up to insert the hand, Figure 7.

4. Discussion

4.1. Developed glove films

When gloves are chlorinated, the polymers vulcanise and cross link, which decreases the physical properties of the materials (force and elongation at break, and tensile strength) (Yip and Cacioli 2002; Sen, Mabuni, and Walsh 2001; Radabutra, Thanawan, and Amornsakchai 2009). However, throughout the gloves manufactured in this study, the materials do not greatly reflect this detriment. In many cases, there is little to no difference in the physical properties when comparing the chlorinated gloves to the control samples. The difference in the results obtained in this study when compared to the results normally shown in industry may be down to the small-scale production. In manufacturing plants, gloves are continuously produced on-line, with going the gloves going through each manufacturing stage in a timely manner (Yip and Cacioli 2002; Akabane 2016; Gamini 2007). However, in this study, the gloves were dipped and chlorinated in batches (two gloves at a time) and then left whilst other gloves were dipped. It is possible that the small-scale, room temperature/humidity, and time left between dipping could have affected the properties of the glove materials. It must also be noted, that more variation (standard deviation) is observed in the control samples made from the thinner materials. In the thicker gloves, the sample with the highest physical properties is the control sample. Therefore, it is likely that the properties were affected by the chlorination, but not as significantly as seen in the industry (Ong 2001; Gamini 2007). The stiffness of the samples is also noted to be softer in the controls (except with

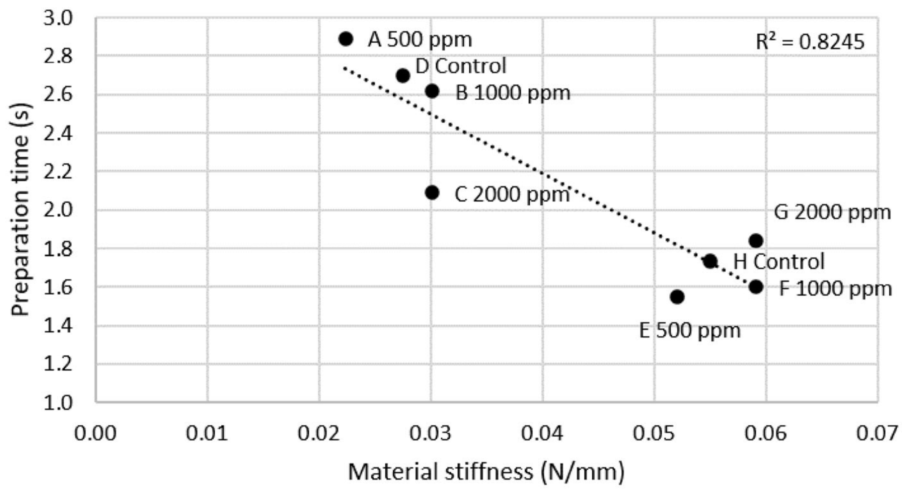

Figure 7. Correlation of stiffness at 100% strain with the preparation stage of the donning process in the dry condition.

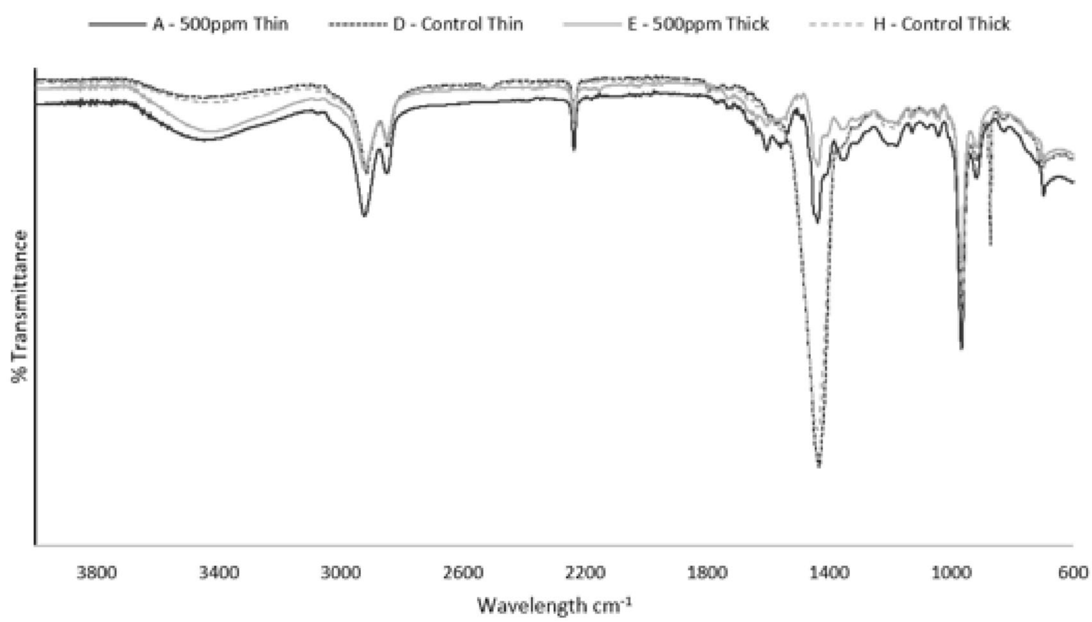

Figure 8. FTIR spectra of developed films showing control samples (D and H) have not undertaken the chlorination process.

the 500 ppm chlorination in the thinner gloves). To highlight that the control sample has not been subjected to any chlorination, Fourier transform infra-red spectroscopy (FTIR) was conducted (Brucker, Nicolet iS10 scanning in the 500–4000 cm^{-1} region) on the developed films. The infra-red (IR) spectra (Figure 8) shows that the control samples (compared to the 500 ppm samples) in this study have not been fully cured. The peaks around 900 cm^{-1} shows the H–C=C bending, which is not present in the chlorinated samples, also the thiol peak (H–S–H) is present in the control at ~2500 cm^{-1}. These peaks show vulcanisation is incomplete, and there is no sulphur cross links present in the control gloves. Without sufficient vulcanisation, the glove film tends to be softer in nature. Consequently, the controls should have superior physical properties, which is observed in much of the physical properties, but not as greatly as expected.

4.2. Donning performance

The chlorination concentration was shown to impact the donning performance. In the dry condition, the higher concentration (2000 ppm) performed quickest out of all conditions. This could be due to the higher concentration making the surface smoother, thus reducing friction (Ong 2001). However, when wet, the 1000 ppm concentration was shown to be quicker to don. This is likely due to the way the chlorinated surface is reacting with the moisture on the surface, giving the

1000 ppm chlorination strength an optimum for a smoother donning experience (Radabutra, Thanawan, and Amornsakchai 2009). In the thicker material the control is quicker to don in both wet conditions, which is likely a result of the powder being present, enabling a smoother transition as the glove is pulled on, which is noted and discussed in previous friction studies (Yip and Cacioli 2002; Manhart et al. 2020).

4.2.1. Thickness

The thickness of the glove affected the time taken to don the gloves, with the thicker gloves taking longer on average to don than the thinner gloves. Significant differences were observed between materials with the 1000 ppm (B–F) chlorination strength. Indicating that this is the only chlorination strength at which gloves significantly affect donning between the thicker and thinner materials. This could be due to it being the minimum concentration needed to reduce the anti-tack properties of the manufacturing process, and provide optimum physical properties allowing the material to be easily pulled over the hand (Ong 2001; Yew et al. 2019). The thicker material was found to be stiffer (almost double) than that of the thinner material. In the donning process, this thought to be easier to don, as the material should be easier to pull down the hand, as there will be less deformation. However, when the thicker gloves are pulled, there will be local regions of friction and localised material bending to the fingers and curves of the hand, meaning that when the material is pulled down the hand, the glove had a tendency to move at the fingers, but roll up on the back of the hand. This was also noted in the previous study assessing donning with different polymer coatings (Preece, Lewis, and Carré 2020). When the gloves are thinner, there is more deformation and conformation to the fingers, leading the gloves to get stuck more in the natural contours. Therefore, to make the glove move further down the hands, the participants spent time pulling the glove from the skin before continuing to pull the glove down the hand. This was much more frequent in the wet condition, which was expected due to the added moisture increasing adhesion of the glove to the skin, increasing both friction and surface area contact (Preece, Lewis, and Carré 2020).

The stiffer materials are indicated to have a positive effect on the 'preparation' stage of the donning process. A strong negative correlation was found, showing that the greater the stiffness, the less time was spent preparing the glove for hand insertion. This is likely because the material is thicker, thus easier to grab, and separate, than the thinner gloves. Furthermore, as the stiffness of the glove material is increased, it is less likely to be subject to creases and folding in the packaging. The thinner materials were visibly more creased and folded. Thus, more time was needed to unfold the material, or mechanically separate the two surfaces. This would also impact the 'hand insertion' stage, which was seen to have moderate correlations between the time taken and the material stiffness. The results also indicate that the less stiff the material, the easier the glove is to stretch over the hand. This both stops the material rolling on the back of the hand and allows a smoother transition of the gloves down the back of the fingers. More participants would be required to draw greater conclusions on how the stiffness of the material impacts the overall donning process.

4.2.2. Moisture

The results show that that the donning process becomes more complex and harder to complete when moisture is present. These results are also shown in similar studies looking at the effects of moisture on force-donning relationships (Pavlovich et al. 1995; Edlich et al. 2003; Côté et al. 1998) and are similar to the results seen in this previous work (Preece, Lewis, and Carré 2020). The concentration of chlorination showing the quickest donning time in both thick and thin materials was with the 1000 ppm chlorination (B and F). In addition to this, glove F showed no significant difference between the dry and wet conditions, although, the wet hand condition took on average 5.77 s longer to don than the dry condition. Most variation between the two conditions is noted in the hand insertion stage, which is to be expected, as at this stage more interaction between skin and glove material occurs. In the thicker gloves, there is a visually smoother transition as the fingers slide down the film in the dry condition. However, when moisture is added, this stage is slower, further indicating that the fingers/hands are getting stuck and the material. This was observed more in the thinner materials, causing issues whereby the participants had to pull harder on the glove and/or pull the material away from the skin where the glove had adhered. Whilst it is clear that moisture adversely affects the donnability of the gloves, there is no clear indication that there is a strength of chlorination that greatly aids or exacerbates this issue. As the donning time was lowest at 1000 ppm but was then greater in 2000 ppm, there is an inference that an optimal chlorination strength is around the 1000 ppm concentration when moisture is present.

5. Conclusions

- Donning the gloves was found to be quicker with chlorination strengths of around 2000 ppm when there is little to no moisture present on the hands. When the hands do have moisture present, the donning of gloves is adversely affected, which is more severe for 500 and 2000 ppm chlorination strength. Chlorinating to 1000 ppm appears to give the optimal conditions for donning when moisture is introduced to the system. This optimum chlorination strength may be brought about by changes in the frictional interactions as well as the bulk material properties.
- The thick and thin gloves each presented their own issues when being donned by the participants. The thicker materials roll up the hand, causing greater constriction. The thinner materials adhere to the hands more, causing the gloves to get stuck. However, overall, the thinner gloves are quicker to don, as the time taken to pull the glove from the skin was quicker than the time taken to unroll the thicker material.
- Further work needs to be conducted into the effects of different material properties on the donning performance of glove materials. The results indicate correlations between the material stiffness and the preparation/hand insertion time. Higher correlations are observable in the preparation time, which is likely a result of less folding in the packaging and less creasing. This means less time is required to mechanically separate the glove materials. Testing gloves that have been manufactured on a larger scale, with a greater number of participants is required.
- Improving the ergonomics of gloves, by investigating the optimum parameters such as thickness and chlorination, can allow industry to develop gloves that are easy to don, increasing user compliance and positive experiences. The use of gloves is salient during the COVID-19 pandemic and changing glove frequently is common practice. This study has highlighted that the chlorination strength is not the only key element in the material donning. The stiffness of the glove materials is shown to be a salient parameter that requires close attention when manufacturing gloves that are easy to don.
- Further studies with similar methodologies looking at the friction and performance with chlorination concentrations between 1000 and 2000 ppm would further indicate how the chlorination and material parameters are affecting the donning performance. Furthermore, as more frequent hand hygiene, and the use of alcohol based hand sanitisers is encouraged, studies should be repeated focussing on different hand conditions (e.g. moisturised, sanitised, etc.).

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