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A quantitative assessment of the extent and distribution of textile fibre transfer to persons involved in physical assault

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Abstract
Knowledge of the number of fibres transferred during a particular activity is essential for the interpretation of findings in similar criminal cases. In this regard, violent contacts and physical assaults still present a challenge, due to a lack of robust published data. Hereby, we present the outcome of an empirical study where different assault activities were simulated by a Jiu Jitsu team and participants were asked to play either the role of an aggressive 'assailant' or a defensive 'victim', wearing cotton garments (i.e., Gi's). Four different scenarios were simulated in replicates (n = 5), each of them involving different intensity levels (low and high) and duration times (30 and 60 s). Results showed that approximately 1,000 to 44,000 fibres were cross-transferred between the

participants' garments, with noticeable differences between the different scenarios. These values were significantly larger than those published in previous works and, therefore, suggested the possibility of a current underestimation of the number of fibres transferred in physical assaults. Furthermore, statistical analysis by ANOVA indicated that the all the variables tested (i.e., intensity level, duration time, and participants role) had a significant effect on the number of transferred fibres ($p < 0.001$) and, consequently, that some knowledge of the case circumstances may be important to make more educated estimations. This is the first time that such a methodology has been applied for the quantitative assessment of fibre transfer between participants in assault activities. Data are expected to help practitioners with the interpretation of findings in real casework and lead to a more robust evidential assessment.

Keywords
textile fibres, forensic, primary transfer, evaluation, likelihood ratio, activity level

1. Introduction

Textile fibres are one of the most important and frequently encountered evidence types in forensic science. Due to the ease with which they transfer during a criminal event, they are particularly helpful in making associations as well as addressing questions of different types, especially at activity level. As such, fibre evidence is mostly exploited in the investigation of the most serious cases involving violence against the person, for both intelligence and evidential purposes. However, despite the large pool of techniques that can be applied in its examination and analysis [1, 2], the interpretation of trace evidence is still challenging [3]. This, indeed, requires a very good understanding and characterisation of the underlying transfer mechanisms.

Several mechanisms can lead to a transfer of fibres between objects [4-7], the simplest of which is direct (or primary) transfer that occurs when a textile makes contact with another surface. In such a situation, the transfer can be one-way or two-way, depending on the nature of the second surface. Typically, a one-way transfer involves a unilateral transfer of fibres from a donor textile to a recipient surface, while a two-way transfer involves transfer in both directions resulting in a cross-transfer between two textiles. Due to the universal use of clothes, two-way transfers are commonly encountered in forensic casework and, especially, in the investigation of assaults and violent crimes against the person. Following contact, the rate at which fibres are typically lost is determined by the time since contact, the nature of the recipient surface, the activity the surface undergoes and, crucially, the initial number of fibres transferred [8]. Therefore, having an estimate of the number of fibres that were (cross-)transferred between the garments immediately after a contact is a key piece of information to inform the interpretation of findings in a specific case.

A number of studies attempted to quantitatively measure the number of fibres transferred through direct contacts. The earliest in the field were mechanistic in nature, i.e., their primary aim was characterising the transfer mechanism itself through the control of physical forces (in addition to the properties of the garments involved). In this regard, the pioneering work of Pounds and Smalldon [4], as well as Kidd and Roberston [9], proved that the number of fibres transferred immediately after a contact between two textiles depends on the pressure applied (up to a threshold), the size of the contact area, the number of repeated contacts, the duration of the contact and the nature of the recipient garment (i.e., how likely the garment is to shed or retain fibres).

Later studies additionally found that this is also affected by the age of the garment [10], the dimensions of the composing fibres [11] and differential shedding [12]. While all these studies were critical in determining the fundamental factors that affect the direct transfer of fibres between two textiles, they also provided some help to inform the interpretation of findings in a practical context. On the one hand they attempted to control a number of variables that are typically difficult to determine from the available contextual information in real casework (e.g., applied pressure). On the other hand, they mostly involved small-scale experiments using only small portions of fabrics and/or without real people involved that, consequently, did not efficiently simulate real case circumstances.

To better assist practitioners, some recent studies applied a more holistic approach by (re-)enacting specific situations and/or activities of forensic interest. In an attempt to inform evidential assessment in the investigation of a real fight, Grieve *et al.* [13] were the first to report data from a simulated person-to-person contact. In particular, they re-enacted the supposed 15-second struggle in a criminal event using the garments seized from the people involved. Results showed that a relatively large number of fibres were transferred immediately after the contact, and that this was higher than expected compared to previous, mechanistic-based, research. The authors, therefore, emphasised the role of simulations in fibre evidence assessment and concluded the need for more studies of this type in forensic literature. Subsequent research that followed this recommendation applied a holistic approach for the study of direct transfers in other commonly encountered activities. Schnegg and Massonnet [14], for example, investigated smothering and strangulation within a domestic setting, whilst Palmer [15] performed simulations of a strangle hold. However, despite their terrific value, published data of this type is still very sparce and incomplete. In particular, little quantitative data is currently available regarding the transfer of fibres in the most violent person-to-person contacts, such as physical assaults and murder attempts.

Therefore, the aim of this study was to strengthen this area of knowledge and, in particular, to simulate a series of physical assault activities with the help of a Jiu Jitsu team. Fights were conducted in pairs, and participants were asked to play either the role of an aggressive 'assailant' or a defensive 'victim', wearing cotton garments (i.e., Gi's). Four different scenarios were simulated in replicates (n = 5), each of them involving different intensity levels (low and high) and duration times (30 and 60 s). This resulted in 20 experiments and 40 datasets, following fibre counting from both the assailant and victim. Thus, fibres cross-transferred immediately after each fight were determined and the effect of the different variables assessed. This is the first time that such a methodology has been applied for the quantitative assessment of fibre transfer between participants in assault activities.

2. Materials and methods

Materials

Eight white, 100% cotton Gi's (= Jiu Jitsu suits) were purchased direct from the manufacturer (Blitz Sport Ltd., adult traditional, 400 gsm Gi, 170cm). The suits consisted of a top with belt fastener and a pair of trousers. To facilitate straightforward discrimination and improve searching accuracy, four of the Gi's were dyed an orange colour (Dylon® All in One Fabric Dye in 'Fresh Orange') and the remaining four a purple colour (Dylon® All in One Fabric Dye in 'Deep Violet'), in order to increase contrast between fibres (Fig. 1). Dying was carried out in accordance with the manufacturer's instructions.

Figure 1 – Example of simulated assault in action. The assailant is dressed in orange and the victim in purple.

Cotton is most commonly encountered type of material in forensic casework. Hence, these suits were considered appropriate for this work. It is known that 'new,' unwashed garments have higher shedability pre- than post-washing. As the process of dyeing the garments included a washing step, any overestimation of shedding was minimised here. Sheddability testing was performed post-dyeing in line with UK casework procedures, i.e., by applying a piece of adhesive tape (sellotape) to the surface of the garment, pressing along its length once only and immediately removing it. The sheddability of the garments was assessed to be 'high' based upon the quantity of fibres on the tape (categories are: non-shedding, poor, moderate and high).

2.1 Assault simulation

Pairs of volunteers from the [*redacted for peer review*] Jiu Jitsu team were tasked to carry out different assault scenarios, wherein one acted as an assailant (orange suit) and other as a victim (purple suit). The assailant was tasked to adopt an aggressive, dominant, stance whilst the victim a more defensive, protective stance. Each simulation measured two parameters: duration (30 or 60 seconds) and intensity (low or high).

- *Low intensity*: a fight with minimal force involving pushing and shoving. Would not usually result in physical injury (see Supplementary Information: Video 1: Low intensity, 60 seconds).
- *High intensity*: an assault relatively more forceful and physically violent involving punching and kicking. Likely to result in physical injury (see Supplementary Information: Video 2: High intensity, 60 seconds).

Thus, four different scenarios were enacted, each involving an 'assailant' and a 'victim'. Each scenario was replicated five times, resulting in 20 experiments and 40 datasets.

Although the participants involved in this present study represented a range of sizes (both height and weight), their physical metrics were not measured. To avoid context specific findings, maintain realism and capture broad variability, participants were shuffled between the experiments, meaning that the same participants were involved in different roles and scenarios.

2.2 Fibre recovery and counting

Clothing from the assailants and victims were examined in separate laboratories using appropriate anti-contamination PPE. The tops and bottoms of the Gi's were examined separately. Prior to examination, the benches were cleaned with Virkon, the surfaces blanked using tapings and laid with fresh brown paper. The garments were removed from the packaging, laid on top of the brown paper and taped (J-LAR™, Shurtape) to collect transferred fibres using a zonal taping method as depicted in Figure 2. The tapes were then secured to clear acetate sheets to permit manual searching.

Each taping was examined under a low power microscope (Leica S6E, x4-20 magnification) for the presence of transferred purple (assailant) or orange (victim) target fibres, as appropriate. Identified target fibres (i.e., fibres clearly showing features of cotton, of the specified colour) were marked on the acetate sheet and manually counted to determine distribution patterns. Eight individuals were involved in tape searching. Each was assigned to one of the eight scenarios, examining the tapings from all five replica experiments, maintaining intra-scenario consistency. Random cross-checks were performed to ensure inter-scenario consistency. Following fibre recovery, the garments were blanked once again and re-packaged as described in section 2.3 ready for the next exercise.

Whilst arguably not as detailed as fibre distribution maps using 1:1 taping, the method of zonal taping is less labour and time intensive than the 1:1 method and produces fibre distribution maps fit for purpose [15]. For this reason, it is often the preferred method of fibre recovery at crime scenes in the UK and the rationale for its use in this study.

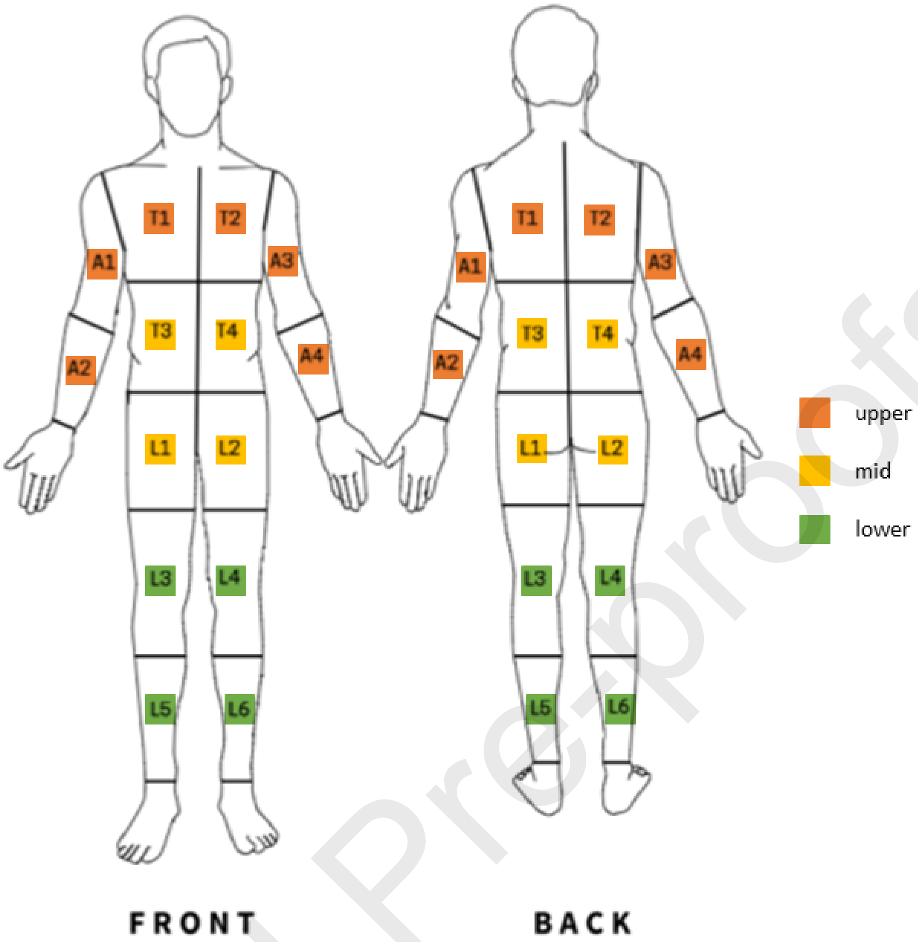

Figure 2 – Sectioning for zonal taping of the garments (GI's).

2.3 Anti-contamination procedures

Strict anti-contamination procedures were followed to minimise cross-contamination. Prior to each exercise the clothing was blanked using J-LAR™ (Shurtape) adhesive tape and the top and trousers placed in individual fresh brown paper bags. The tapes were retained, but not examined. During each simulation participants were instructed to stand in diagonally opposite corners of a mat (38 - 48 m^2) and were handed their packaged suits, into which they changed. Following the simulation, the participants returned to their corners, and immediately removed and packaged the top and trousers separately in brown paper evidence bags for examination. The mats were not cleaned in between each assault, due to the large surface area of the fighting area, high expected number of transferred fibres and inclusion of five replica studies to account for variability. Moreover, not all assaults were conducted on the same day. The mats on which the assaults took place were tidied away at the end of each day and reset for the next occasion.

2.4 Statistical analysis

Multifactor (three-way) analysis of variance (ANOVA) was conducted to assess the contribution of each of the three tested variables (i.e., intensity level, duration time, and participant role) to the variation of the number of fibres. For this, data were initially fitted using a generalised linear model with fixed effects, which included main and two-way interaction effects. Given that the number of fibres transferred between garments previously showed deviations form normality, different probability distributions (i.e., normal, Poisson and negative binomial) were tested and compared for their goodness of fit using various assessment metrics, including the log-likelihood, Akaike information (AIC) and Bayesian information (BIC) criteria. Subsequently, the negative binomial distribution was chosen, as it systematically led to the lowest values for all of them (data not shown).

Type-III (partial) sums of squares were used in ANOVA. This computing method was preferred to Type I or II mainly because it is a more robust choice for over-parameterised models and, therefore, a better alternative to correctly model the significant interaction effects that were observed between the three independent variables. As a generalised linear model was used instead of an ordinary least-square one, traditional metrics for measuring the effect sizes (such as the eta-squared) could not be used. Instead, the effect sizes were directly estimated through the likelihood ratio chi-square statistics.

2.5 Software

All data analysis was performed using RStudio Desktop, version 2023.03.0-386, with R base software, version 4.2.3. In particular, the following packages were used: “stats” for the fitting of the generalised linear models, “car” for the calculation of the type-III ANOVA table, “vcdExtra” for the assessment of the model goodness-of-fit.

3 Results and discussion

3.1 Assessment of the fibre total counts

Following the enactment of each fight, the number of fibres transferred was counted from all the participants` clothing via zonal taping. Table 1 shows the summary statistics for the observed total fibre counts, while Figure 3 shows their distributions across the simulated scenarios. Overall, a transfer of fibres occurred between the participants in all the enacted fights and, in each case, this transfer was two-way, i.e., from the assailant to the victim and from the victim to the assailant. For each way (victim to assailant *or* assailant to victim), the number of fibres transferred was relatively large and ranged from 1,071 to 44,613, with a grand mean = 13,434 and median = 6,630 (Table 1). These values far exceeded those of any previous person-to-person transfer study published in the literature [4, 9, 10, 13, 16], with the only exception of Palmer [19]. Whilst direct comparison is impossible and so must be treated with caution, to provide some context, the quantities reported in this study are 10-fold that reported in mechanistic studies.

The observed data spread was also relatively large, with an average relative standard deviation of 34 %. This, however, was in line with previous works [14, 16], as well as authors` research experience, and, therefore, not surprising. The high variability in the observed number of fibres transferred between garments reported in previously published works is typically due the high number of undetermined and uncontrollable factors that play a role in the transfer mechanism. Here, specifically, the large data spread was likely because, in an attempt to mimic real life conditions, minimal direction and limited constraints in relation to movement were provided to participants, which subsequently led to five unique and individual assault activities for each of the four simulated scenarios.

Table 1 - Summary statistics for the fibre total counts observed in each simulated assault scenario. Each scenario has been replicated 5 times.

Variables			***Fibre total count***				
Role	***Intensity***	***Duration***	***Min***	***Max***	***Mean***	***Median***	***SD***
Assailant	*Low*	*30 s*	1,071	1,899	1,354	1,191	338
Victim	*Low*	*30 s*	1,400	11,003	5,301	5,191	3,616
Assailant	*High*	*30 s*	3,775	5,940	4,789	4,780	773
Victim	*High*	*30 s*	7,922	29,920	20,670	21,643	8,528
Assailant	*Low*	*60 s*	4,679	11,034	7,111	7,196	2,564
Victim	*Low*	*60 s*	4,313	8,036	5,756	5,237	1,417
Assailant	*High*	*60 s*	15,308	44,613	31,921	31,368	11,095
Victim	*High*	*60 s*	24,040	39,508	30,569	26,717	7,745

Figure 3 – Distribution of the fibre total counts observed in each simulated assault scenario. Each scenario was replicated 5 times.

3.2 Effect of controlled variables

Data were compared between scenarios. Perhaps as expected, a systematically higher number of fibres transferred between the participants was observed in high intensity fights compared to low intensity fights, and in longer fights compared to shorter fights (Fig. 3). Intensity, in this study, represents pressure, movement and repeat contacts, all of which have been demonstrated to increase fibre transfer [4, 9] and thus these findings were expected. Regarding the effect of the participant role, significant differences in the number of fibres transferred from the assailant to the victim and from the victim to the assailant were also observed, but their characteristics were very dependent on the duration time. In particular, higher total fibre counts were typically observed on the victims` clothing than on the assailants` clothing in shorter fights, thus also supporting a larger transfer of fibres from the assailant to the victim than from the victim to the assailant. The inverse was true in longer fights (Fig. 3). Interestingly, a very pronounced imbalance was observed between the number of fibres counted on the assailant and victim in shorter, high intensity fights. In this case, the number of fibres transferred from the assailant to the victim was observed to be much higher than those transferred from the victim to the assailant. This difference was significantly larger than that observed in any other scenario. It is not clear why there is such a difference and further research would be needed to determine the cause. However, these results do demonstrate that preliminary information on the intensity level and duration time may be helpful in real casework to shape more accurate expectations on the fibre transferred in a specific assault case.

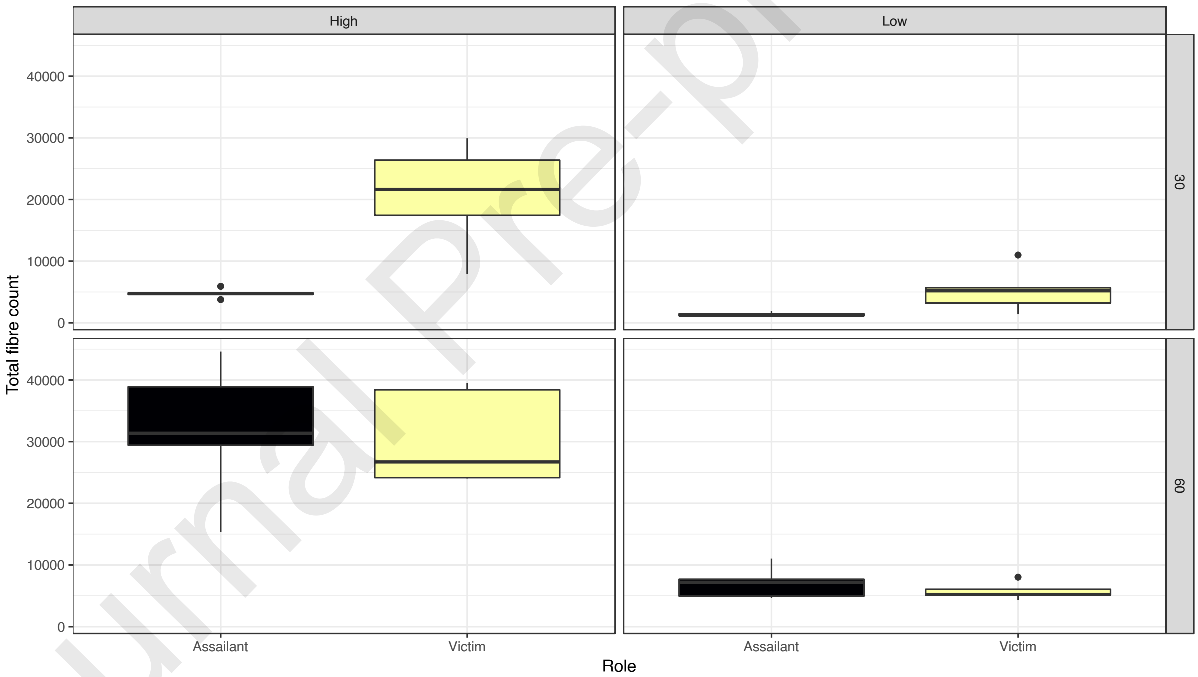

Figure 3 – Distribution of the fibre total counts observed in each simulated assault scenario. Each scenario was replicated five times.

For a more objective assessment of the contribution of each of the three controlled variables (i.e., intensity level, duration time and participant role) to the fibre total count, data were modelled through a generalised linear model and statistically analysed by analysis of variance (ANOVA). Table 2 shows a summary of the main outputs, while Figure 4 shows the related main effects and two-way interactions plots. The results perfectly aligned with previous observations. Indeed, each of the three controlled variables showed to have a statistically significant main effect ($p < 0.001$) on the fibre total count (Table 2). The participant role and duration time also had a significant two-way interaction effect ($p < 0.001$), thus also further supporting a very strong dependency between these two variables. No statistically significant two-way interaction effect was observed between participant role and intensity level, as well as between intensity level and duration time. However, the respective interaction plots did not completely exclude a mutual dependence, even if modest (Fig. 4d-e). Likelihood-ratio chi-square statistics showed that the main effect of the duration time was the most important in magnitude, followed by the main effect of the participant role, the interaction effect between participant role and duration time, and the main effect of the intensity level (Table 2).

Table 2 – Summary table for the ANOVA of the generalised linear model inferred on data. P-values near 0 support the hypothesis that variations in the related variables are significant on the fibre total count, while p-values close to 1 support the hypothesis that the related variables are not significant.

Variable	***LR chi square***	***p-Value***	***Significance [a]***
Role (R)	56.7	< 0.001	XXX
Intensity (I)	40.6	< 0.001	XXX
Duration (D)	91.4	< 0.001	XXX
R x I	0.4	0.546	
I x D	1.5	0.214	
R x D	47.8	< 0.001	XXX

[a] *"XXX" = p < 0.001, "XX" = p < 0.01, "X" = p < 0.05*

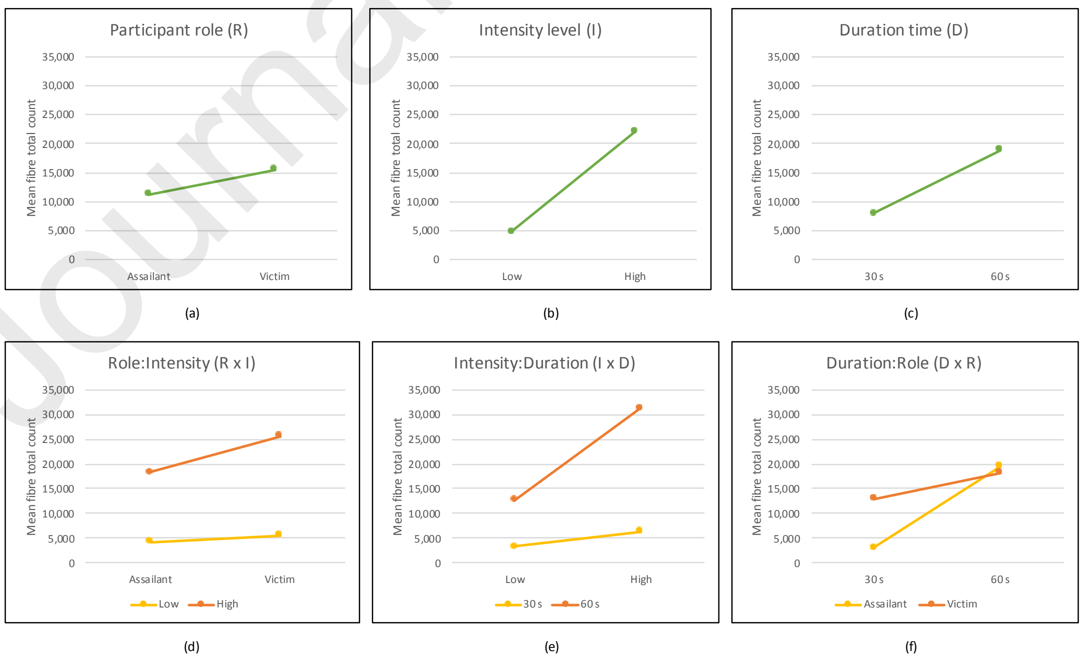

Figure 4 – Plots of the mean outcomes (in terms of fibre total count) for each independent variable by combining the effects of the other two variables (i.e., main effects plots, a-c) and

by separating the contribution of one other variable (i.e., two-way interactions plots, d-f). For main effects plots, non-horizontal lines indicate that a main effect may exist. For two-way interactions plots, non- parallel or intersecting lines indicate that an interaction effect may exist. In both cases, refer to the ANOVA table in Table 2 for statistical significance.

3.3 Fibres spatial distribution on garments

The fibre distribution across the different sampled areas of the garments was analysed in greater depth. Figures 5 and 6 show heatmaps of the averaged fibre numbers and percentages (over the total counts), respectively. Predictably, the largest proportions of fibres in each scenario were counted on the upper areas and/or front sides of the garments. This is likely because these areas were most frequently in contact during the fights. The overall percentage of fibres collected from the mid and lower areas was smaller compared to the upper areas (grand means: upper = 56.8 %, mid = 26.1 %, lower = 17.1 %), and (even if to a lesser extent) from to the back side compared to the front side (grand means: front = 57.8%, back = 42.2 %). The participant role and duration time did not seem to significantly affect the fibre distribution across the different scenarios, but the same was not true for the intensity level. Indeed, a clearly larger proportion of fibres were collected from the upper areas compared to the mid/lower areas after a low intensity fight, while a slightly more homogeneous distribution was observed after high intensity fights. This was likely ascribable to the larger number of interpersonal contacts in high intensity fights compared to low intensity fights. From the perspective of real casework, this is a very important observation, as it suggests that both upper and lower garments warrant examination.

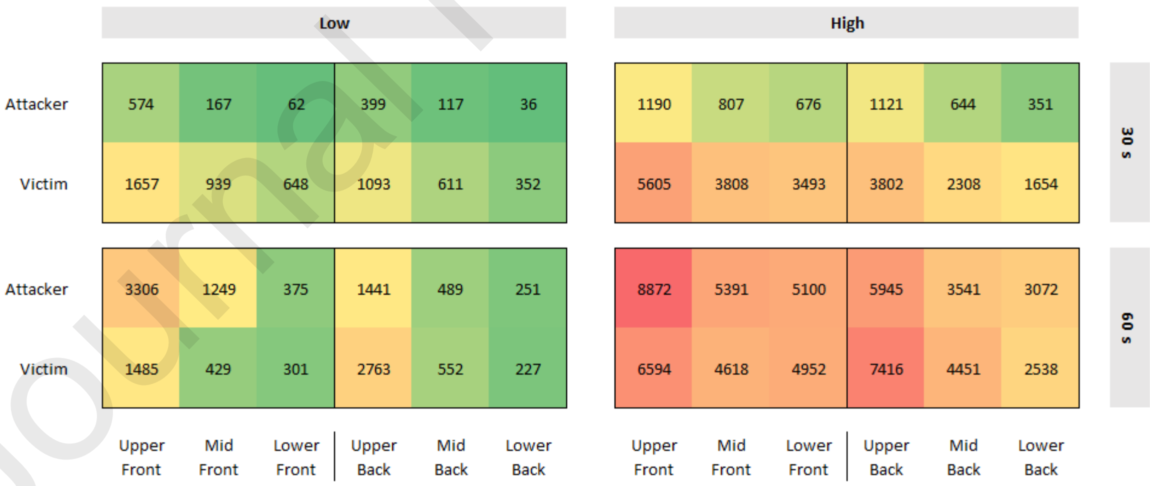

Figure 5 – Heatmap of the average fibre number observed on each sampled garment area, as a function of the assault scenario.

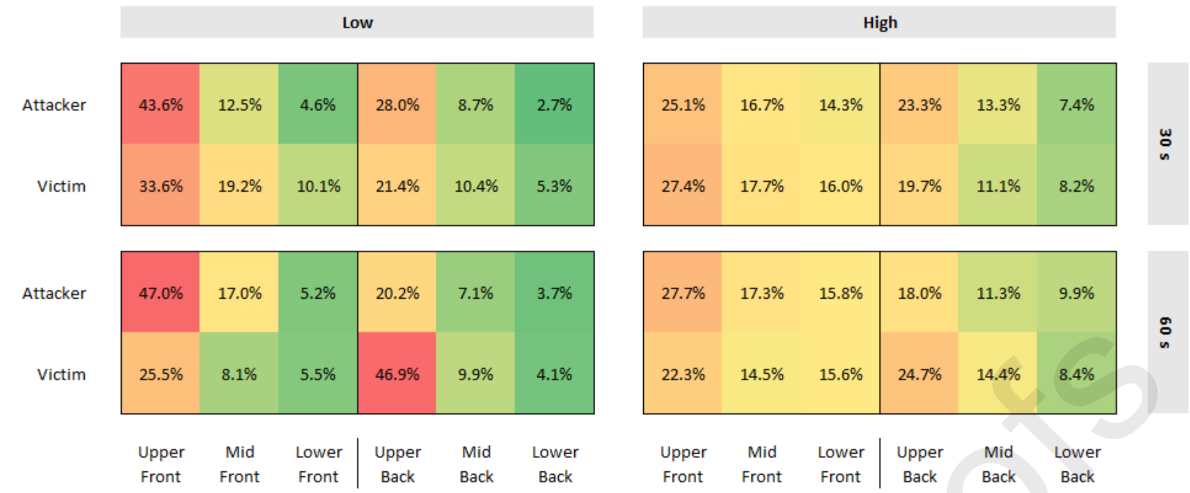

Figure 6 – Heatmap of the average fibre percentage (over the total count) observed on each sampled garment area, as a function of the assault scenario.

Fibre distribution maps, generated using a zonal taping approach, showed higher quantities of fibres transferred to the upper, front body in line expectations, as those areas received the most contact. This demonstrated in casework, inclusive of packaging of the garments prior to examination, inference can be made from areas where large fibre quantities are found with intense activity, although it may not be the case with small numbers of fibres.

The correlation between the number of fibres sampled from each garment area, as well as between them and the fibre total count, was studied and Figure 7 reports the respective Pearson correlation coefficients (PCCs). Generally, PCCs > 0.80 and PCCs > 0.90 were observed between the different sampled areas, and between them and the fibre total count, respectively. These findings supported a relatively high degree of correlation between the number of fibres collected from each area across the scenarios. This suggests the possibility that, in casework, the total fibre count may be predicted based on a limited number of examined areas, if the specific relationship between them is known. This may be an interesting research perspective for future work that could potentially lead to time efficiencies in garment examination. A grand mean = 0.90 was calculated, while the average PCCs between areas on the same and opposite garment sides (i.e., front and back) were 0.94 and 0.85, respectively. This meant that the number of fibres collected from areas on the opposite sides of the garments correlated slightly worse than those collected from areas on the same side.

	Upper Front	Mid Front	Lower Front	Upper Back	Mid Back	Lower Back	Total
Upper Front	1	0.94	0.88	0.84	0.82	0.84	0.95
Mid Front		1	0.93	0.83	0.87	0.86	0.96
Lower Front			1	0.83	0.87	0.86	0.95
Upper Back				1	0.92	0.82	0.93
Mid Back					1	0.85	0.94
Lower Back						1	0.91
Total							1

Figure 7 – Correlation plot between the different sampled areas, as well as between them and the total count.

5 Conclusion

In this study, the number of fibres cross-transferred between cotton garments during a physical assault has been determined by simulating different situations through the help of a Jiu Jitsu team. Results showed that, approximately, 1,000 to 44,000 fibres were cross-transferred between the participants' garments, and that each of the controlled variables (i.e., intensity level, duration time and participant role) statistically affected the number found. Overall, these values were significantly larger than those published in previous works and, therefore, also suggested the possibility of a current underestimation of the number of fibres transferred in physical assaults. Furthermore, the differences between scenarios indicated that some knowledge of the case circumstances may be important to provide a more precise estimate in real cases and improve the reliability of the interpretation process.

A key design of this study was to mimic real-life situations frequently encountered in casework, whereby the exact circumstances are often unknown, and each case is different. The findings will enable practitioners to be more cognisant of the potential scale of fibre transfer from person-to-person contact involving cotton fibres and provide broad boundaries that can be used to inform case expectations and pre-assessment. Noteworthy, some discrepancies in fibre transfer quantities were found between this study and those previously published. This suggests that there is a potential gap in understanding of transfer mechanisms, and more studies are needed to improve the interpretation of findings. Whilst this study has performed a baseline evaluation of fibre transfer in physical assaults, that should now be built on with subsequent investigation of persistence characteristics.

6 Acknowledgments

This work has been approved by the [*redacted for peer review*] Research Ethics Subcommittee of [*redacted for peer review*] (reference no. 1089). It was conducted in accordance with the ethical standards established in the Declaration of Helsinki and informed consent was obtained from all participants before enrolment in the study.

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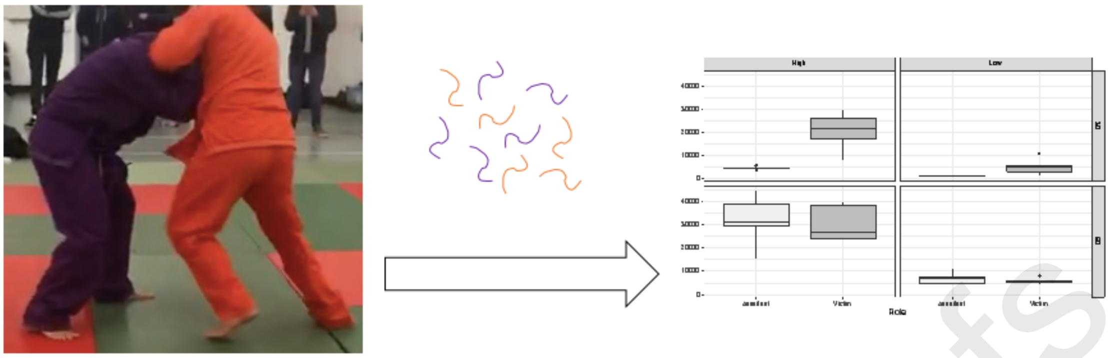
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30000
20000
10000
0
Victim
Role

Highlights

- Fibre transfer from unconstrained physical assaults involving human subjects
- More fibres transfer in person-person contact than previous data suggests
- Realistic fibre transfer quantities to inform better decision making
- Care must be taken in assigning ‘roles’ in physical assaults using fibre evidence
- Broad fibre distribution maps evident despite garments stored in paper bags

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