The Dibber: Designing a Standardised Handheld Tool for Lay-up Tasks

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Figure 1. (a) The Dibber is a standardised handheld tool with multiple features to fit the requirements of lay-up tasks. (b) Our tool helps laminators performing manual tasks that involve forming layers of plies to a mould and (c) replace the need to own multiple handmade tools.

ABSTRACT

We present an application of engineering and ergonomics principles in the design of a standardised tool, The Dibber, which is a tool with multiple geometric features to fit the diversity of lay-up tasks used in the composites industry. The Dibber is the result of a design process, which consists of a series of observations and prototyping to extract geometric requirements for lay-up tasks. To demonstrate that it is possible to design a standardised tool prototypes of the Dibber were distributed and 91 participants gave feedback. Our results are positive and show consistent patterns of use across industry sectors, as well as between novice and expert laminators.

Author Keywords Handheld tools, Standardised tools, Design, Aerospace industry, Composites manufacturing.

1. Introduction

This paper presents the design process for a standardised handheld tool (Figure 1a) to be used in the manufacture of advanced composites. Composite materials have applications in various sectors, e.g. autosport, aerospace and marine. Driven by these sectors (Lewis, 2013) it is anticipated that the manufacture of composites products will require higher rates of production, at a lower cost and consistent quality (CLF, 2013; Crowley et al., 2013a; Lewis, 2013).

This is a challenge because currently the dominant manufacturing process for the composites industry is a flexible but unstandardised process called hand lay-up (Newell et al., 1996). Predominantly this is a skilled manual process that involves forming layers of plies to a mould by a laminator, i.e. the person doing the job (Figure 1b). Typically the plies are reinforcements of glass or carbon fibre preimpregnated with resin (prepreg).

Hand lay-up relies on the capabilities of a laminator's hands. The laminators have the freedom to develop their own techniques and personal toolkits (Figure 1c) for tasks based on tacit knowledge (Chatzimichali et al., 2013). Leading to more than one technique and an unstandardised process (Bloom et al., 2013; Elkington et al., 2013). To increase standardisation and consequently production rate, increased levels of knowledge regarding lay-up are required (Chatzimichali et al., 2013). This understanding has resulted in research aimed at deconstructing hand lay-up (Bloom et al., 2013; Elkington et al., 2013). It has also motivated a move towards automation in the composites industry (Newell et al., 1996).

The development of a knowledge base on hand lay-up is of particular value for the manufacture of small, complex and varied geometries (Chatzimichali et al., 2013; Crowley et al., 2013a), lay-up is still the most economic and productive route to date (Ward et al., 2011b). In addition this knowledge base can support lay-up standardisation and production where the cost of automation is prohibitive e.g. small batch or in smaller companies (Crowley et al., 2013a).

Observations of the composites industry, specifically of aircraft components found that ergonomic and design for manufacture principles associated with manual tasks were not accommodated in the design of composite components (Kayis et al., 2005). Additionally their research also observed a lack of training, understanding of posture and best working practice for lay-up tasks has implications for the health and safety of a laminator (Kayis et al., 2005).

Therefore studying composites design from the perspective of a laminator is a novel subject that can contribute knowledge to support both a laminator and the composite design process.

1.1 Laminators and Hand Tools

A commonly observed industry practice is for laminators to hand make and personally own their own hand tools (Figure 1c). Therefore it is challenging to identify how lay-up tasks are currently performed with these tools. Initial research suggests hand tools help laminators to form prepreg to specific geometries (Elkington et al., 2013; Kayis et al., 2005). However the use of personal tools presents risk, due to resin contamination, and in practice there are attempts to prohibit their use.

Whilst there are some commercially available hand tools for lay-up (Airtech 2015, 2016; Bojo, 2011; LamRight, 2013), it is believed their ability to support the composites industry and the training of laminators is limited by the lack of any formal understanding that surrounds the use of these tools. Additionally the observation that laminators persist in making their own suggests the designs are not adequate, and that laminators are reluctant to cease ownership of their tools. Previous research on hand tools in the composites industry found that a designed tool was adopted by laminators in one company, when they were involved in the design process (Kayis et al. 2005).

It is important to consider this research by Kayis et al. because previous attempts to standardise the lay-up process, through automation and the use of regulated manufacturing aids, has resulted in the younger generations of laminators having different levels of motivation to more experienced laminators. (Crowley et al., 2013b) This is because they may perceive themselves to be marionettes rather than craftsmen (Crowley et al., 2013b).

1.2 Designing Hand Tools

Previous research on the design of hand tools has integrated both functional and ergonomic requirements for a range of production and domestic applications (Aptel et al. 2002; Cacha, 1999; Li, 2002; Tichauer and Gage, 1977). The use of hand tools with ergonomic design principles has demonstrated higher working efficiency (Lewis and Narayan, 1993).

The introduction of ergonomics into tool design requires the participation of a user, a tool and the workplace in the design process (Aptel et al., 2002; Gjessing et al., 1994; Kayis et al., 2005; Restrepo et al., 2009). Therefore the design process of the hand tools requires the involvement of both functional analysis and prototyping through iterative stages (Aptel et al., 2002; Marsot and Claudon, 2004). Prototyping allows the users and workplace to interact with the design process before a design is fixed (Aptel et al. 2002), facilitating the acquisition of expert knowledge and user insights and the assessment of user requirements (de Bont et al., 2013). It has also been found that for designers to make technical decisions about a tool's usability it is necessary to involve expert users (Farel et al., 2013). To improve quality from the users perspective and support decision making during the design process different design methods have been used (Haapalainen et al., 1999/2000; Marsot, 2005, Marost and Claudon, 2004). However in all of these examples the use of a tool for a particular task is defined and the tool’s user does not make their own tool.

Designing hand tools in the composites industry presents distinct challenges because their functional requirements are not defined and to date there has been a lack of research effort to understand laminators’ requirements. Therefore their design requires eliciting and structuring a laminator’s knowledge to understand why laminators currently make the tools they do. Previous research has stated the value of using artefacts to elicit tacit knowledge (Rust el at., 2000). Therefore the design process in this research will use prototypes to involve laminators and elicit their tacit knowledge and define functional requirements for the tools.

2 Aims, Objectives and Scope of the Paper

To address the current challenges facing the composites industry this research is concerned with improving the process of composites design. The approach taken was to investigate the hand tools of laminators, to understand how a laminator’s needs can be supported along with the industry.

Therefore the aims of this work were to:

- Extract design requirements for a standardised tool. Study 1 (Section 4) presents the initial observations and experimental exploration to address this aim.
- Evaluate a functional prototype with laminators working in the field. Study 2 (Section 5) presents an evaluation stage to address this aim.
- Develop the initial knowledge base around hand tools by engaging the composites industry and a wider variety of laminators using a functional prototype of a standardised tool. Study 2 (Section 5) addresses this aim.

3 Materials and Methods

The Dibber (Figure 1c) is a standardised multi-feature tool that was designed and evaluated through a user centred approach in two stages (Figure 2): observation of laminators and prototypes formed an experimental exploration to design a functional prototype that was evaluated through a large scale study with 17 different groups of users.

In the following of the paper text in italics corresponds to participants’ feedback or transcriptions of observations.

Figure 2. Overview of our methodology to design and evaluate a prototype for a standardised handheld tool

4 Study 1: Designing a Functional Prototype

4.1 Observation and Description of the Design Space

4.1.1 Participants

Sixteen participants in four different contexts with a range of experience (Table 1).

Table 1. A summary of the observations that were conducted

4.1.2 Procedure

In all of the observations the laminator's tools were used to engage the participants in conversation. Observations and conversations from the visits were recorded manually and supplemented with sketches or photographs, if they were allowed.

Observation 1 is distinct. A day was spent observing a laminator in a laboratory environment rather than production. For the lay-up task we choose a mould geometry that is representative of an aerospace component and captures most of the difficulties associated with lay-up (Ward et al., 20011a). A 600 mm by 400 mm U shaped mould geometry which has a 25 mm high ramp inclined at 30º was used (Figure 3a). Our observations from industry suggest that tool use is most prevalent on tight internal corners and edges, features which this mould geometry captures. The laminator was video recorded (Panasonic HC-V500) forming a ply ten times to the mould geometry.

Figure 3. Observation 1: (a) The mould geometry observed, (b) with different tools being used to form different features

Additionally in Observation 1 technology probes were used with the objective of inspiring the laminator and researcher to think about how the tools could be different (Hutchinson et al., 2003). This is because whilst it may be true that laminators feel they can make whatever tools they like, they are limited by available material, time and what they have seen other laminators use before or have inherited. The probes were material samples that had been made, to explore the physicality of the hand and what could make the lay-up process easier. They focussed on how the hand could be extended without restricting its movement, and therefore the material samples referenced articulated armour (Wallace Collection, 1900) and second skins (Hess, 2013). Two types of probes were developed, one used fake nails to build a hard surface that could articulate (Figure 4aii) and the other elastic to build soft bulbous surface that could articulate (Figure 4aii).

They were introduced after the laminator had conducted their lay-up tasks. After their introduction, the laminator generated drawings and demonstrations for how the tools could be attached to the hand.

Figure 4. Observation 1: (a) The material samples that were used as technology probes. (bi) The laminator's drawings and (bii) demonstration for how tools could be attached to the hand.

4.1.3 Results

Table 2 presents the results from the observations of the laminators and their tools. It shows the personal and handmade tools belonging to sixteen different laminators.

Table 2. The results of observing the laminators

Figure 3 shows how the tools that the laminator selected from their toolset were used to form different parts of the mould geometry. It shows how the tools are gripped and supported through the palm of the hand to be used during lay-up. They also show how different tool geometries are used with different actions on different mould geometries.

The technology probes allowed the laminator to imagine how tools could be attached to the hand for lay-up (Figure 4b) and discuss the physicality of the hand as demonstrated by the following quote. "Do you think if every surface on the hand was hard it would be easier to laminate? *With the soft regions of your hand you can sense*. If the hard regions could sense? *Yes, but if it didn't hurt.*" During the demonstration of how to attach tools to the hand the laminator showed and discussed how to couple shapes of different tools with actions (Figure 4bii). The knife shaped tool should be rolled and the flat edge tool smoothed. The rolling action rather than the scoring action is important because it prevents the tool damaging the ply. It was observed that attaching the tools to the hand could allow each laminator to use a specific tool with a specified action. This is because each tool could only be gripped through the palm in a manner that allowed either a rolling or smoothing action to be comfortably used, but not both.

4.1.4 Discussion

Examination of the tools in Table 2 shows that they have a range of geometries, a range of materials and a range of names *"dibbers", nurkers"* and *"squeegees"*.

The variation in geometries is because "*tools are made for jobs"*. They are made in response to a mould geometry, therefore the variety in tool geometries indicates the range of mould geometries that the laminator has worked with, particularly highlighted by the complete tool set in Figure 1c. However *their identity is not fixed and can evolve to enable any lay-up task to be performed satisfactorily*. The observations showed that laminators use different shaped tools to perform the same lay-up task suggesting there is also an element of personal preference.

It was found the variation in materials is for different reasons. The tool's materials as a contaminate drives a culture for *"carbon only tools"* (Observation 3) and customer requirements for *"HDPE only tools"* (Observation 4). Fine mould geometries mean laminators source and adapt metal parts (Observation 2 and 3). However in reality the laminators use what they can find or make, most commonly a hard plastic, typically PTFE (Observation 1, 2, 3 and 4). PTFE is prevalent since it can be easily sourced and has a low surface friction with prepreg.

The tools are considered vital for their job. It was found their success is judged if they provide a laminator with the following functional requirements:

- *"Comfort",* lay-up is a manual task and a laminator is required to repeat tasks all day and be able to continue the next day.
- *"Geometry matching"*, the range of mould geometries the laminators have to form is beyond the capabilities of the average hand.
- *"Additional force",* the perceived force required for forming plies is beyond what they can apply with their hands. There is currently little understanding or definition of the force required to deform different prepregs, therefore what the laminators use in practice is a result of their experience and perception of what is required.

Additionally a tool has to meet the following functional requirements:

- *Material,* the tool needs to be fabricated in a material that satisfies both a customer and laminator. A laminator has a preference for a material that provides ease of use, whilst a customer requires a material perceived as a non-contaminant.
- *A standardised approach,* for the use of tools. From the observations it can be seen that the tool's geometry, material and action for use are influenced by the variables of the laminator, the mould geometry, the prepreg and the context.

4.1.5 Intermediate Prototyping

We made 12 intermediate prototypes (Figure 5) to investigate the five requirements that were stated in Section 4.1.4:

- Comfort, geometry matching, additional force, material and a standardised approach.

Table 3 presents that materials that were used to make the prototypes.

Table 3. The materials used to make the intermediate prototypes

Figure 5a shows the prototypes that focussed on exploring comfort, geometry matching, additional force and material. Prototypes 1, 2 and 3 developed the material samples used as technology probes. Whilst Prototypes 4, 5, 6 and 7 incorporated materials with a range of compliances and geometries.

Figure 5b shows the prototypes that focussed on exploring a standardised approach. These prototypes were developed from the laminator's sketches (Figure 4bi) to be attached to the hand. Prototypes 8, 9 and 12 can be put on a finger or thumb, and Prototype 11 over the knuckles to be used with a smoothing action. Prototype 10 can be put a fingertip and used with a rolling action.

Figure 5. The 12 intermediate prototypes to explore (a) comfort, geometry matching, additional force and material requirements and (b) the standardised approach requirement.

4.2 Testing Intermediate Prototypes

4.2.1 Participants

The participants were two researchers who were investigating hand lay-up. One participant had never used a tool for hand lay-up before.

4.2.2 Procedure

The 12 intermediate prototypes made in Section 4.1.5 were tested by being used for a lay-up task. The first lay-up task was performed without any tools.

The lay-up tasks were observed and video recorded (Panasonic HC-V500). Discussions and observations were recorded using hand written notes. The tasks involved forming a ply to a range of mould geometries, a 45º internal corner with a 3mm radius of curvature and a 60º internal corner with a 30 mm radius of curvature (Figure 6). These mould geometries were selected because they capture a range of curvatures for corners and edges.

Figure 6. The mould geometries that were used to observe the prototypes. (a) A 45° internal corner with a 3mm radius of curvature (b) A 60° internal corner with a 30mm radius of curvature.

4.2.3 Results

Table 4 presents the results from the observations of the prototypes. During testing it was found that the prototypes could only be used on certain mould geometries. In Table 4 the mould geometries where results were recorded reflects this finding. The observations were classified using the requirements for tools that were extracted in Section 4.1.4. They were classified using the following guidelines:

- *Geometry matching:* the prototype's geometry was found to be suitable or not. If a prototype was not tested on a mould geometry, it can be assumed the geometry was not appropriate.

- *Comfort:* the prototype was used with ease or the use of the prototype made the lay-up task easier.
- *Additional force:* There are no results classified for additional force. This is because in the experiment only one weight of prepreg was used. This requirement is triggered when the prepreg becomes heavier, therefore it was not expected for this requirement to become triggered.
- *Material:* The prototype's material was found to be suitable or not.
- *Standardised approach:* The prototype was used with a specific action on a particular mould geometry.

Table 5 presents why a tool is required for the range of mould geometries that were observed. It integrates the observations from the laminators' tools and prototypes to identify what the tool's requirements are for a particular mould geometry.

Table 4. The results of the 12 intermediate prototypes (Figure 5) for different lay-up tasks.

Table 5. Why is a tool required? The geometrical features of the moulds observed with a hand or features of a tool that enable its manufacture

4.2.4 Discussion

The results in Table 4 show that different prototypes could be tested on different mould geometries. It is believed this is because different mould geometries have different requirements for a tool. This belief is further demonstrated by differences in how the results are classified between the mould geometries. For external mould geometries the results are predominantly classified by comfort and material requirements. Whereas for flat and internal mould geometries the results are predominantly classified by geometry matching, comfort and material requirements.

The testing showed that on a flat mould geometry the geometry matching requirement was fulfilled when a prototype had a flat edge. On tight internal edges a point was required. However a high number of challenges were seen with the prototypes' meeting this requirement. This suggests that a tool's geometric requirements for use on a specific mould geometry were not fully captured in these prototypes.

The results show that there were differences in how the prototypes met the comfort requirements for flat and internal mould geometries and external mould geometries. For flat and internal mould geometries there was a focus on whether the prototype could be gripped and used with ease. Whereas for external mould geometries there was a focus on a prototype making the lay-up task more comfortable through the use of a deformable material rather than the participant's hand.

For all mould geometries the prototypes that were attached to the hand had challenges with meeting the comfort requirements. This was because of the prototypes' weight and ease of use. In addition of flat and internal mould geometries comfort challenges also arose from how the prototype could be gripped and therefore its ease of use.

For all of the mould geometries the material requirement was met when the prototype could be gripped with ease. This occurred when the prototype was made from a rubber (with varying densities) or a hard but deformable plastic. In addition the material requirement was satisfied when the prototype's material did not stick to the prepreg. It was found this was when the prototype's material was rubber with a surface texture. However there were challenges with a prototype's material when use of the prototype made the lay-up task more difficult. This was because rubber (with no surface texture), syntactic, latex and silicone all stuck to the prepreg. This suggests there is a strong correlation between a prototype's material and comfort requirements.

In Table 4 there were some results classified for standardised approach. It is believed the comparatively low number of results with this classification can be attributed to the experiment design. The prototypes were provided without instructions on their use. However the results that captured a standardised approach requirement indicate what prototypes are intuitively used with a certain action.

For all of the mould geometries the standardised approach requirement was met when the prototype had a feature with a long flat edge. On a flat mould geometry the prototype was used with a smoothing action whilst on the internal and external mould geometries the prototype was used to pin the prepreg in place during lay-up.

Table 4 shows that more prototypes could be tested on flat and internal mould geometries than external mould geometries. This result is supported by the observations of laminators and the mould geometries on which they commonly use hand tools. This therefore indicates tool use is more of a geometric necessity on some mould geometries, rather than a bias in the prototypes' designs.

In Table 5 the different requirements for tools are presented. To reflect the number of results from the testing it is only possible to include three requirements: geometry matching, comfort and material.

Table 5 has extracted from the results and above discussion how each of these requirements can be met for different mould geometries, and has prioritised them. The requirement's priority is represented by the ordering in the table. The results suggested that the requirements for comfort and material are connected, therefore their priority should be viewed as equal.

For flat and internal mould geometries the geometry matching requirement has the highest priority. This is because the results suggest if the geometry is not suitable the usefulness of the tool is limited. Whereas for external and large curved mould geometries comfort and material requirements have the highest priority. This is because the results indicate it is not a geometrical necessity to use a tool of these geometries.

4.2.5 Secondary Prototyping

We created five secondary prototypes (Figure 7), from rubber, PTFE, acrylic and neoprene.

The aim was to design a universal hand tool. Therefore this secondary prototyping focussed on integrating into one tool the requirements for the different mould geometries that were tested. The geometry matching, comfort and material requirements were extracted and prioritised from testing the intermediate prototypes.

For flat and internal mould geometries the geometry matching requirement had the highest priority. Therefore for flat mould geometries all the secondary prototypes integrated a long edge and for internal mould geometries a narrow flat edge with a point was incorporated. The previous results suggested there was a need to define a tool's geometric requirements. Therefore to allow this focus these long edges and narrow flat edges on the secondary prototypes were made from PTFE, the material that laminators current use to make their tools. This decision also supported the material requirement for not sticking to the prepreg. For these mould geometries the other material requirement for allowing the tool to be gripped with ease was met by selecting a rubber for the handle. To meet the comfort requirements these secondary prototypes could be gripped through the hand to use and control either the long edge or the narrow flat edge with ease.

For external mould geometries comfort and material requirements had the highest priority. To meet the comfort requirement and ensure the lay-up process was made easier a deformable surface was integrated. The form this surface took was either the prototype's handle with a dual purpose (Figure 7a) or a surface that could articulate and conform to the curvature required by the mould geometry (Figure 7b, c and d). To be compatible with the material requirement of not sticking to prepreg a rubber with surface texture was selected.

To continue exploring the standardised approach requirement of having certain shaped features used with specified actions three of the secondary prototypes could be attached to the hand (Figure 7c and d). The results from the intermediate prototypes suggested there were challenges with the weight if the prototype was attached to the hand. Therefore one of the secondary prototypes (Figure 7d) was articulated in an attempt to make it lighter.

Figure 7. The five secondary prototypes developed and tested during hand lay-up. (a), (b) and (d) all show one prototype whilst (c) shows two prototypes that were designed to be used together. Rubber, PTFE, acrylic and neoprene materials can be seen in all the prototypes, and the images of the prototypes in use give an idea of how they were gripped.

4.3 Testing Secondary Prototypes

4.3.1 Participants

The participants were two researchers investigating hand lay-up, one of whom had not used tools before, and an expert laminator.

4.3.2 Procedure

The five secondary prototypes developed in Section 4.2.5 were observed during a lay-up task (Figure 7). The mould geometry had a 45° angle ramp with an internal and external radius of curvature of 3 mm (Figure 6a). Five lay-up tasks were undertaken, one with no tool and four with the developed secondary prototypes (two of the prototypes were used in one lay-up task, Figure 7c). The tasks were undertaken once and then this sequence was repeated two more times. A starting point for the lay-up (Bloom et. al (2013), Elkington et al. (2013)) and initial instructions on how the prototypes were provided but instructions guiding how the prototype should be used were not stipulated, to encourage unexpected discovery. Observations made in this way have often been a driving force for ideas regarding a tool's use (Sennett, 2008).

The lay-up tasks were observed and recorded using a video recorder (Panasonic HC-V500), and the participants' opinions and conversations were recorded using hand written notes. Due to the fact there is no agreed quality rank for hand lay- up, assessing the quality achieved using the different prototypes is challenging. Therefore the data collected was the participants' opinions on the prototypes.

4.3.3 Results

The results from testing the prototypes will be structured to consider how the different prototypes met the requirements for different mould geometries.

For flat and internal mould geometries it was found the long flat edge and corner features integrated into the prototypes met the geometry matching requirements. However it was found the long flat edge could not be used with ease. This was because the area that could be gripped to control this feature was not wide enough. This result has implications for the geometric design of a tool. The surface perpendicular to the long flat edge needs to be longer.

In addition it was found that prototypes attached to the hand did not meet comfort requirements. The prototype in Figure 7c was too heavy, and the prototype in Figure 7d could not be used with ease. This result has implications for how the standardised approach requirement can be realised.

It was also found that the thickness of a prototype affected the prototype's ease of use. The prototypes' features were easier to use when the prototype had a thicker grip, with a three dimensional form rather than being flat. Of particular note is the form of the prototype in Figure 7b.

The selection of rubber to make a conformable grip met comfort requirements. All the prototypes met the material requirements as PTFE presented no challenges during use.

For external mould geometries it was found the articulated features were not used with ease. This result is aligned with the earlier observation that there are mould geometries where the use of hand tools is not commonly observed. This result implies that the requirements of external mould geometries should not be considered in future prototyping.

4.3.4 Discussion

From the results of the prototype testing it is believed a prototype can meet the geometry matching, comfort and material requirements for both flat and internal mould geometries. The results also indicate that if geometry matching is not a requirement for a mould geometry then a tool might not need to be designed for them.

However the results suggest that the standardised approach requirement cannot be met by constraining how a tool is used, by attaching it to the hand. It is believed to realise the standardised approach requirement a tool's design needs to include how to use a tool's feature. Observations made by the participants highlight the need to couple the prototype with instructions. This quote *'feels like the right thing to do whatever that may be'* demonstrates the intuitive but uninformed way the prototypes were handled during their testing. Without instructions development of a technique for handling a tool remains intuitive. This has implications for:

- Further testing, an element of play associated with the prototypes will prevail

- Supporting a laminator during the decision making process in lay-up. Without instructions a laminator is unsupported, and it is believed the standardised approach requirement can't be meant.

The coupling of a tool and an instruction set suggests a solution borders on the realm of training and skill acquisition.

4.3.5 Prototyping

Figure 8 presents the prototype design, the Dibber, which developed from the results of testing the secondary prototypes.

The results of testing the prototypes suggest that a tool's design should focus on meeting the requirements for flat and internal mould geometries. To meet the geometric requirements the following features should be incorporated: a long flat edge (Feature 1) and a point (Feature 2). To meet the comfort requirements the following features should be included:

- A conformable grip.
- A varying thickness so the tool is a three dimensional form in the hand (Feature 5).
- A wider surface perpendicular to the long flat edge so the tool can be gripped and used with ease. It was decided that the wider edge of this surface should be curved to form another geometry matching feature and make the prototype easier to grip (Feature 4).

These features were discussed with a laminator. This quote, *'want every surface to be useful, and do something the hand cannot do'*, demonstrates that the laminator believed it was not necessary to incorporate a conformable material for a grip into a tool. Therefore it was decided that the entire prototype should be a hard material. This offered the opportunity the replace a conformable grip with another feature for the geometry matching requirement (Feature 3). It was decided this should be curved because of how a tool would sit in a hand to use the other features and for curved mould geometries.

This prototype, the Dibber, has focussed on the form of a tool to meet geometry matching and comfort requirements. To maximise our engagement with participants and test the form, this prototypes was fabricated using injection moulding. Therefore due to manufacturing constraints it was not possible to incorporate the result of PTFE meeting the material requirements from previous testing.

Figure 8. The Dibber's different features.

5 Study 2: Evaluations

We performed a large-scale study to evaluate the Dibber. Over 330 Dibber were produced using injection moulding and distributed to laminators and composite production companies, from November 2014 until summer 2015.

5.1 Participants

Of the 330 prototype distributed, 86 laminators from 13 different contexts (3 training, 8 production in a marine, aerospace and cross sectors and 5 countries, 2 research labs) contacted us and provided feedback. In addition 5 participants were from 4 contexts that are outside of composites: 1 leather trimmer, 2 art fabricators, 1 picture framer and 1 art historian. Our goal behind this was to explore if the Dibber could also be used by other industries.

5.2 Procedure

Participants were asked to give feedback on how they used the Dibber as well as any modifications that they made or any difficulties they experienced with it. We used various methods to collect participants' feedback. Most of them communicated via email, but we were also able to arrange visits to 5 production and 3 training facilities in order to have a discussion with participants around their use of the prototype. Messaged feedback consisted of a written description and an optional annotated photograph of the Dibber. During the visits we recorded conversations and demonstrations, using written notes, and gathered images of the prototype in use, using drawings or the camera and video on an iPhone 5s, as well as drawings made by the participants.

5.3 Analysis

To better understand how the Dibber was manipulated, we used the participants' feedback to generate annotated images that we then fed to an algorithm to generate heatmaps representing trends in uses and modifications.

5.3.1 Image Generation (Hand Annotation)

Two types of image were created. The first one describes how participants used the prototype, and the second how they modified it (or suggested to modify it). These images were either generated by the participants themselves (drawn or from a photograph of the prototype) or constructed by the experimenter by using the feedback. In particular we extracted and colour-coded 6 categories of *feedback feature* describing how they used the Dibber:

1. Features most commonly liked/ used
2. Features like because they help to move the tool around in the hand
3. Features not liked
4. Features which present no additional help compared to other own tools
5. Features not used due to material issue
6. Features not used due to lack of guidance

Additionally we extracted 5 categories of *feedback feature* describing how they modified it (or suggested to modify it):

7. Features modified by adding material
8. Features modified by removing material
9. Features modified due to wear after multiple uses
10. Features requiring a different material
11. Features requiring guidance on how to use them

If the feedback did not correspond to an entire feature but a particular aspect, only the appropriate area of the feature was colour coded.

Each image was also tagged with a description of the participants including level of expertise (expert or novice) and sector.

5.4 Results

In total, we gathered 72 annotated images of the Dibber. These images correspond to the number of participants summarised in Table 6. In total we had 91 unique participants but the number of tests in Table 6 are higher for both how the prototype was used and modified. This is because we spoke to some of the participants twice over a period of approximately 3 months, or the participants made more than 1 suggestion. The results are discussed with reference to features of the Dibber that are labelled in Figure 8.

Table 6: Number of tests from which we generated annotated pictures of the Dibber

5.4.1 Similarity/Disparity between Novice and Expert Users

We did not have any novice participants for sectors outside of the composite industry, but for composites sectors we observed differences between novice and expert users. Figure 9 shows the heatmap of the parts of the Dibber the participants most used/liked. Although there is a general trend to like Feature 3 (16% of novice tests and 10% of expert tests) and Feature 1 (61% of novice tests and 21% of expert tests), novices liked Feature 4 more (86% of tests). This can be explained by differences in how using a tool is approached. Novices are more experimental, often they *just want to try something*. This also suggests that novices did not know what to do with the device so need additional guidance, as demonstrated by the following observations.

In 5 of the 17 different contexts the participants mentioned that they wanted more guidance on how to use the tool. 2 of these contexts were novice participants in training. It was felt how to grip and use the tool *was not intuitive*. However it was found that expert laminators required additional *guidance to be convinced about trying the tool in preference to their own*.

Figure 9. Parts of the Dibber the participants most liked or disliked

Both novice and expert users liked the form of the prototype and Feature 5, saying it helps to move the tool around the hand easily (not represented on Figure 9). However Figure 9 shows they also disliked the top edge (61% of novice tests and 63% of expert tests) and Feature 2 (64% of novice tests and 65% of expert tests). Discussions with laminators suggest that both of these features are too sharp. The sharpness of Feature 2 has *prompted* *concerns about damaging the material,* and the top edge *needs rounding* so the edge is more comfortable in their hand.

We also observed slight differences in the tool modification as shown on Figure 10. 12% of expert tests suggested modification by adding material all around the edges. The reasons why participants suggested modifying the complete edge is because *they wanted a tool that is capable of handling the scale of the parts seen in production*. They suggested *having the same tool on two different scales*. Also up to 33% of the novice tests suggested modifying Features 3 and 4 of the Dibber by adding material. These tests with novices also suggested to modify Features 3 (up to 33% of tests) and 4 (up to 70% of tests) by removing material. However these novices had experience from a previous training session using a *teardrop shaped tool* so it possible that this is shaping their feedback.

Figure 10. Parts of the Dibber modified (or suggested to) by adding or removing material

Other modifications consisted of removing (filing) material and these focussed on the top edge (48 % of novice tests and 46% of expert tests) and Feature 2 (59% of novice tests and 22% of expert tests). 6% of expert tests also filed Feature 1, this was because there were concerns *an unfiled edge would mark or damage the material*.

5.4.2 Similarity/Disparity between Sectors

We also observed differences between sectors (Figure 11). All tests from sectors outside of the composite industry (6) gave positive feedback. Only 3 tests modified or suggested to modify the tool by filing Features 1 and 2 to make them fit to their task, all these modifications came from the leather trimming sector. It was felt Features 1 and 2 *were a little too sharp*, so might damage the leather.

In comparison the participants from the composite sectors made more use of Feature 4 (up to 18% in the aerospace and 62% in the marine and cross sector), but participants from marine and cross sector did not like Feature 2. All the sectors used Feature 1 (aerospace 18% of tests, marine and cross sector 67% of tests, other sectors 33% of tests) and Feature 3 (aerospace 17% of tests, marine and cross sector 7% of tests, other sectors 17% of tests) to varying degrees. Differences in how the prototype was used between sectors could reflect differences in the geometries that require forming, or differences in what the participants' feedback focussed on.

Figure 11. Parts of the Dibber the participants most liked or disliked based on their sector

5.4.3 Effect of Material

We observed several comments about a non-adequate material used for the tool. There are two reasons for that. The first one is that the tool's material could be changed to facilitate lay-up (less friction between composite material and tool). This type of comment came from laminators. The second one is the material should be changed to avoid contaminating the composite material, and introducing the risk of defects. This type of comment came from either laminators or part owners, and is driven by a customer's specification. Note that all these comments came from expert participants. Figure 12 shows the feedback coming from aerospace or marine and cross sector and we can observe that different edges are highlighted, confirming the idea that different sectors have used the tool in different manners.

Figure 12. Part of the prototype where the material was not adequate and needs to be changed, for experts in aerospace and marine or cross sectors.

6 General Discussion

The results of this study demonstrate that it is possible to capture geometry matching and comfort requirements for flat and internal mould geometries in a hand tool's form. The results of testing the Dibber suggest that the point of Feature 2 should be soften to enhance the design, and rounding the edges on the grip (Feature 5) will increase the comfort associated with the tool's use.

However the results suggest that it is a necessity of a tool's design to integrate material requirements. Testing the Dibber demonstrated that meeting this requirement requires an understanding of the interaction between a prepreg, a hand tool's material and any limitations specific to a particular production environment.

This study has found that the standardised approach requirement cannot be met through the form and material of a hand tool. This work proposes that addressing the standardised approach requirement requires the consideration of skills and training around handling hand tools. Based on this observation a taxonomy was structured that included how to use the different features on the Dibber (Table 7). The taxonomy was populated using the results from the large scale study. Using the taxonomy it is proposed that standardising approaches for lay-up tasks become part of the design process for composite components, and demands that design for manufacture strategies are built (Jones et al. 2015).

Table 7. A taxonomy is proposed to support the standardised approach requirement, and integrating the design of a hand tool into the design process of a

composites component. The taxonomy has been populated with results from the large scale study.

The taxonomy also functions as a design aid for project base solutions to be realised (Crowley et al., 2013a). This is required because of the wide range of mould geometries that exist within legacy products and it is envisaged will continue to be developed. It is important to note the dynamic state of this taxonomy. It is by no means complete, and is limited by the lay-up tasks that were observed. It aims to demonstrate initial thoughts on a way in which the knowledge base developed through the study in this work can be represented. Therefore a necessary feature of the taxonomy's design is a mechanism to integrate a laminator's feedback into its development. It is possible to imagine the taxonomy being extended to include material requirements.

The additional force requirement was not captured in the design of the Dibber, however the observation that 2 participant noted that their tool had worn suggests that this requirement should be considered. This is not consistent feedback, therefore it is important to understand if it is the tool's material or how the tool is being used that is resulting in the wear. It is possible that the force the tool is used with is not consistent across the participants and this contributes to the tool wearing. Currently within the field there is not a clear definition of how much force is required to form a composites part, making it challenging to judge if the tool is being used with too much force. However investigating force variation between participants would provide an understanding of what is seen in practice to form different weights of prepreg, and allow the additional force requirement to be captured in a tool's design.

6.1 Future Work

We are interested in an instrumented Dibber, using advanced sensors, capable of generating data to describe its spatial position and also build an understanding of the additional force requirement. This includes collecting data on what the device is doing, where it is doing it and the force being applied. Developing an instrumented tool fits with research that is being conducted by ergonomics communities to classify performance (Barber et al., 2015), and the HCI communities investigating manual tools that can reinvent the interface between design and manufacture (Willis et al., 2011) and augment the skills of users (Zoran et al., 2014).

These findings from our research open opportunities for more studies to explore how to design and implement a strategy for handheld tools that are supportive to standardisation. We also believe our work will interest design communities such as HCI and provides researchers with a method that can be used to evaluate shapes of traditional tools or modern tools, e.g. changing the shape of mobile devices or tangible devices to fit in the user's hand at task.

7 Conclusions

Our work contributes a significant step towards understanding why laminators make the tools they do. To understand the founding principles behind the adoption of certain geometries for specific objects and tasks in context, we developed and evaluated a manual tool for laminators in the composites industry. The results of our large scale study suggest that it is possible to design a standardised tool for hand lay-up tasks. In particular we found consistent patterns of usage of geometries of the Dibber across industries and expertise levels with no difference for handedness. Our results suggest that we transferred a part of the tacit knowledge of an expert user into our tool which is not only relevant for the manufacturing industry but also has consequences for many tasks that cannot be automated and still require a user.

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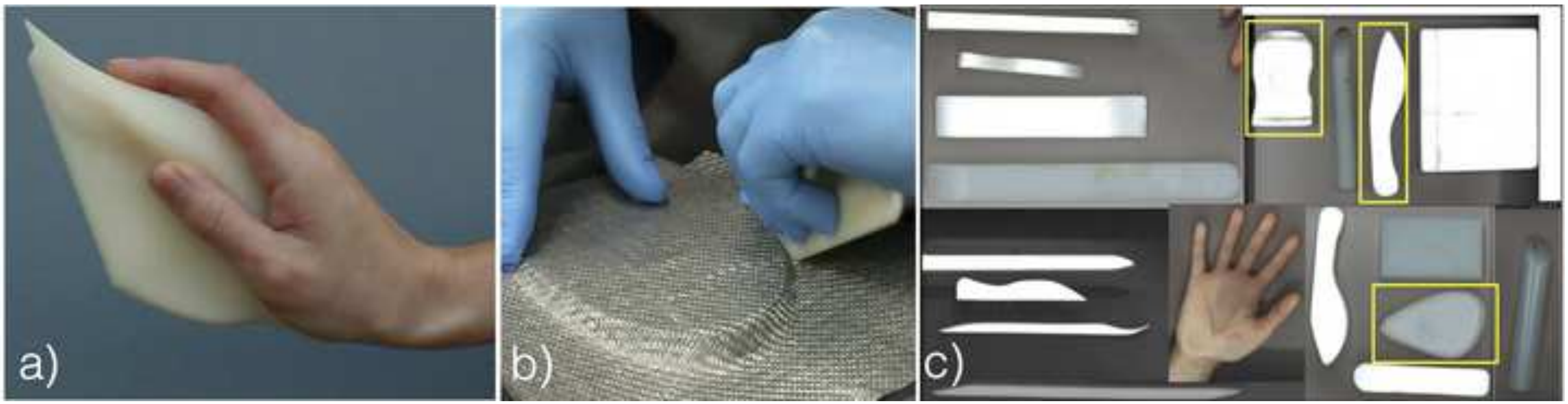

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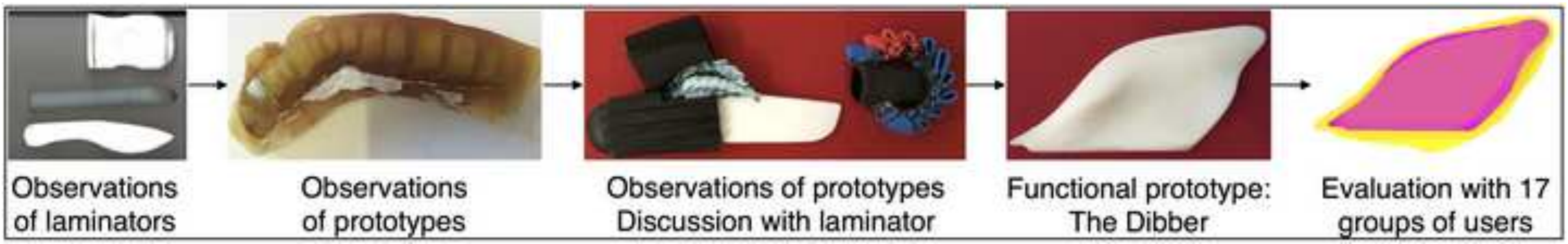

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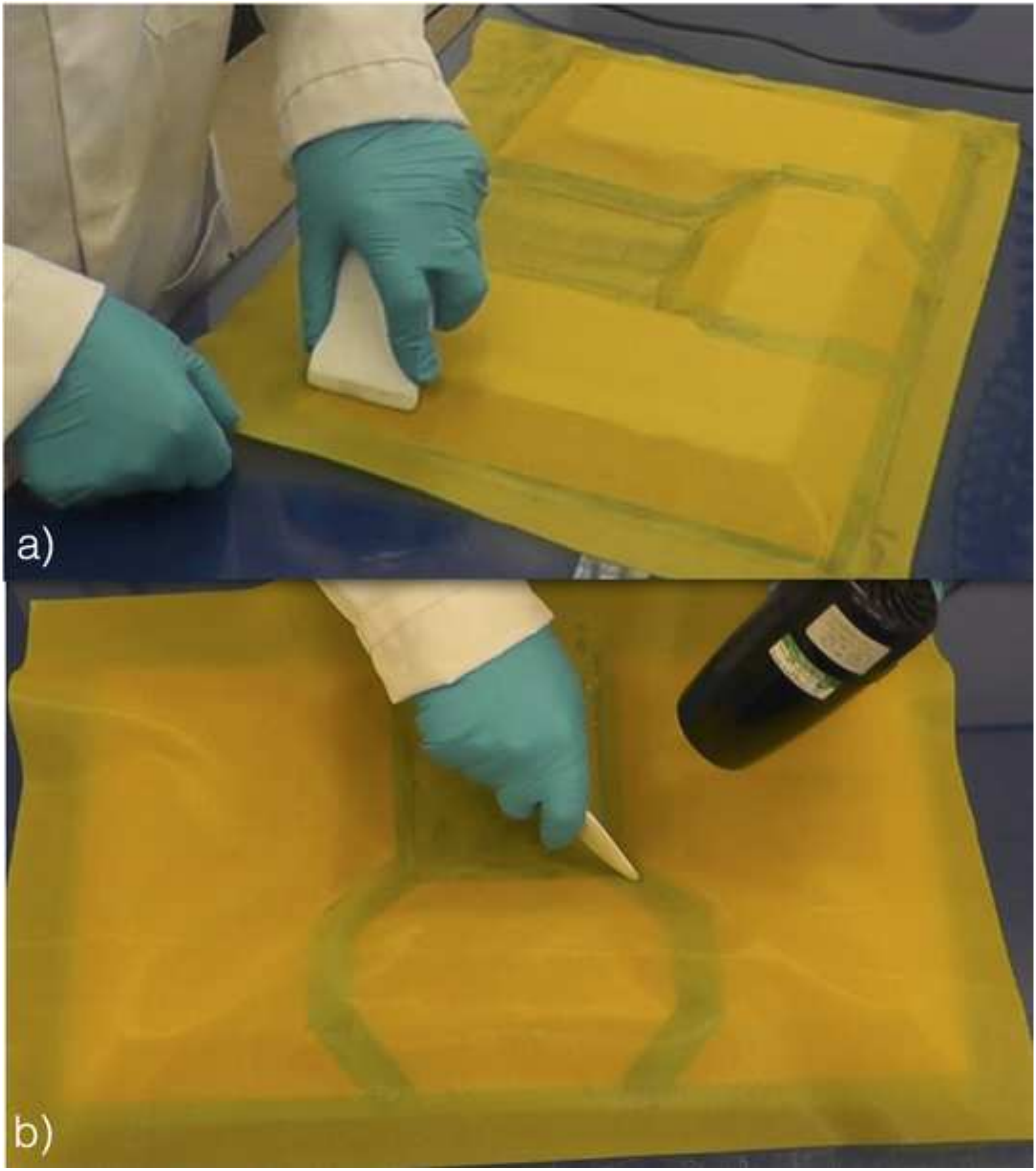

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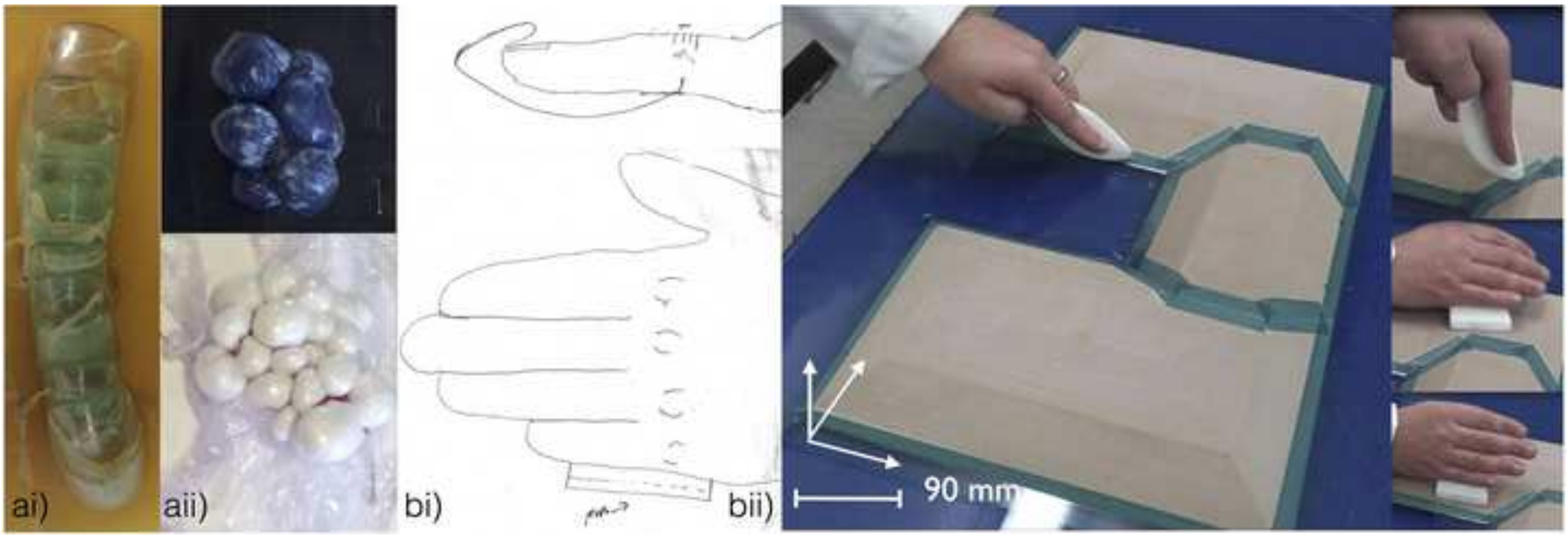

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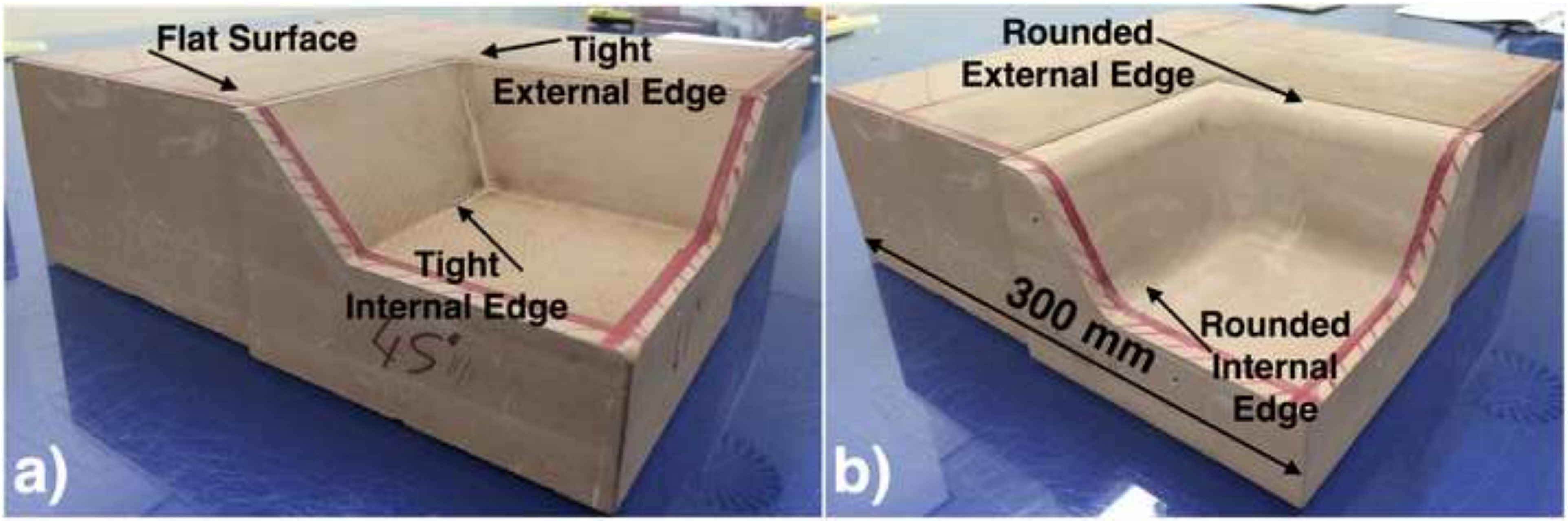

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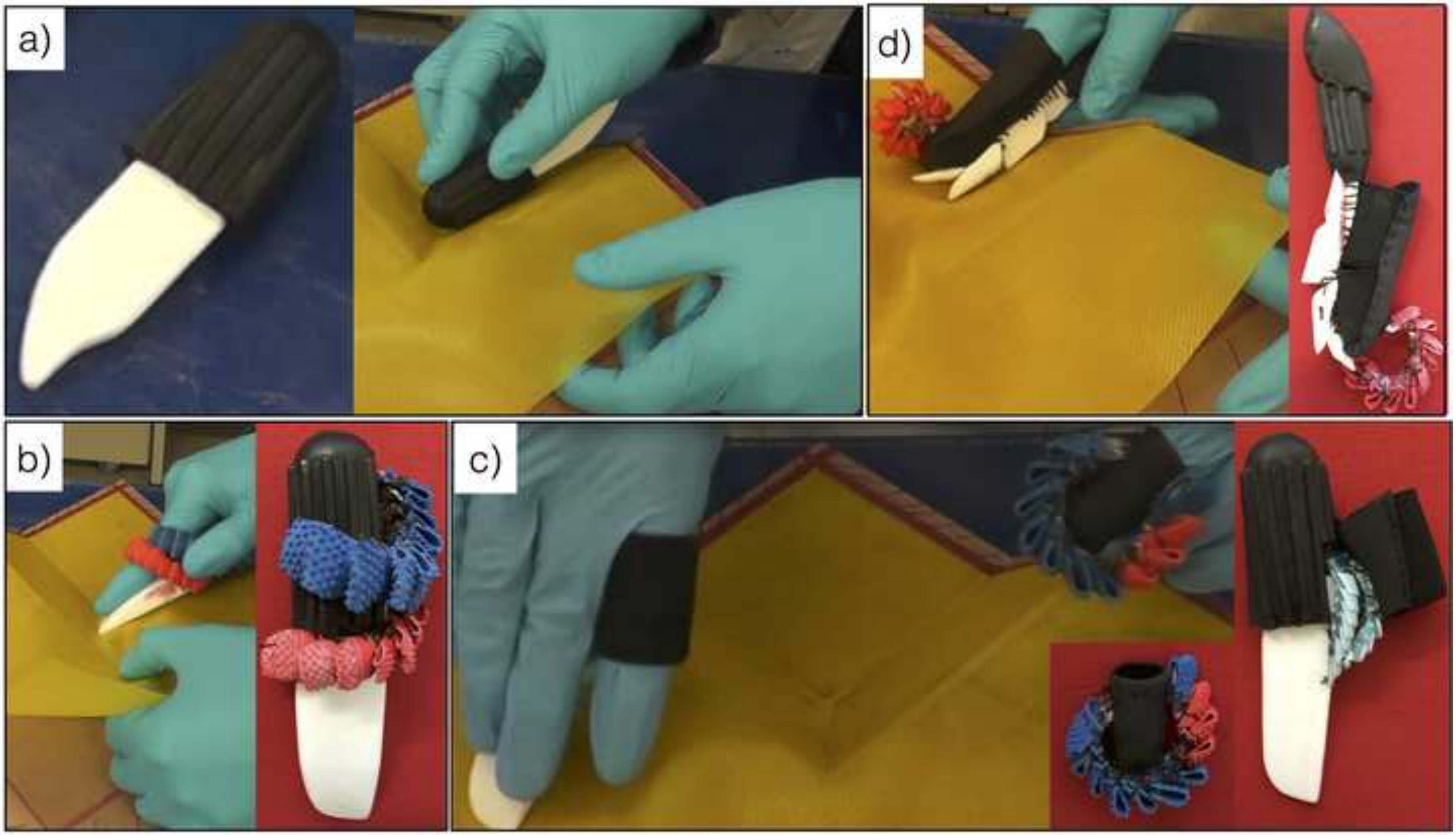

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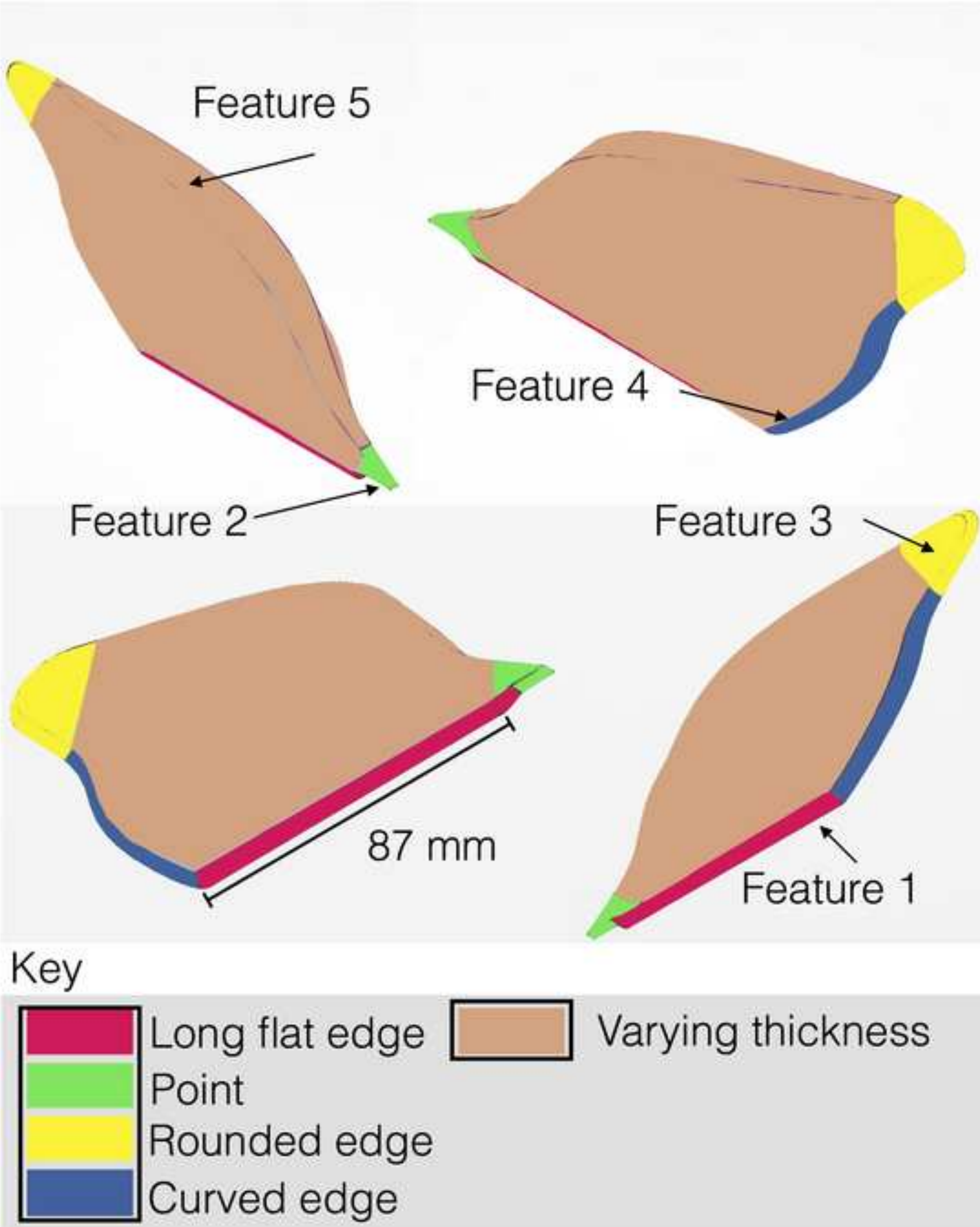

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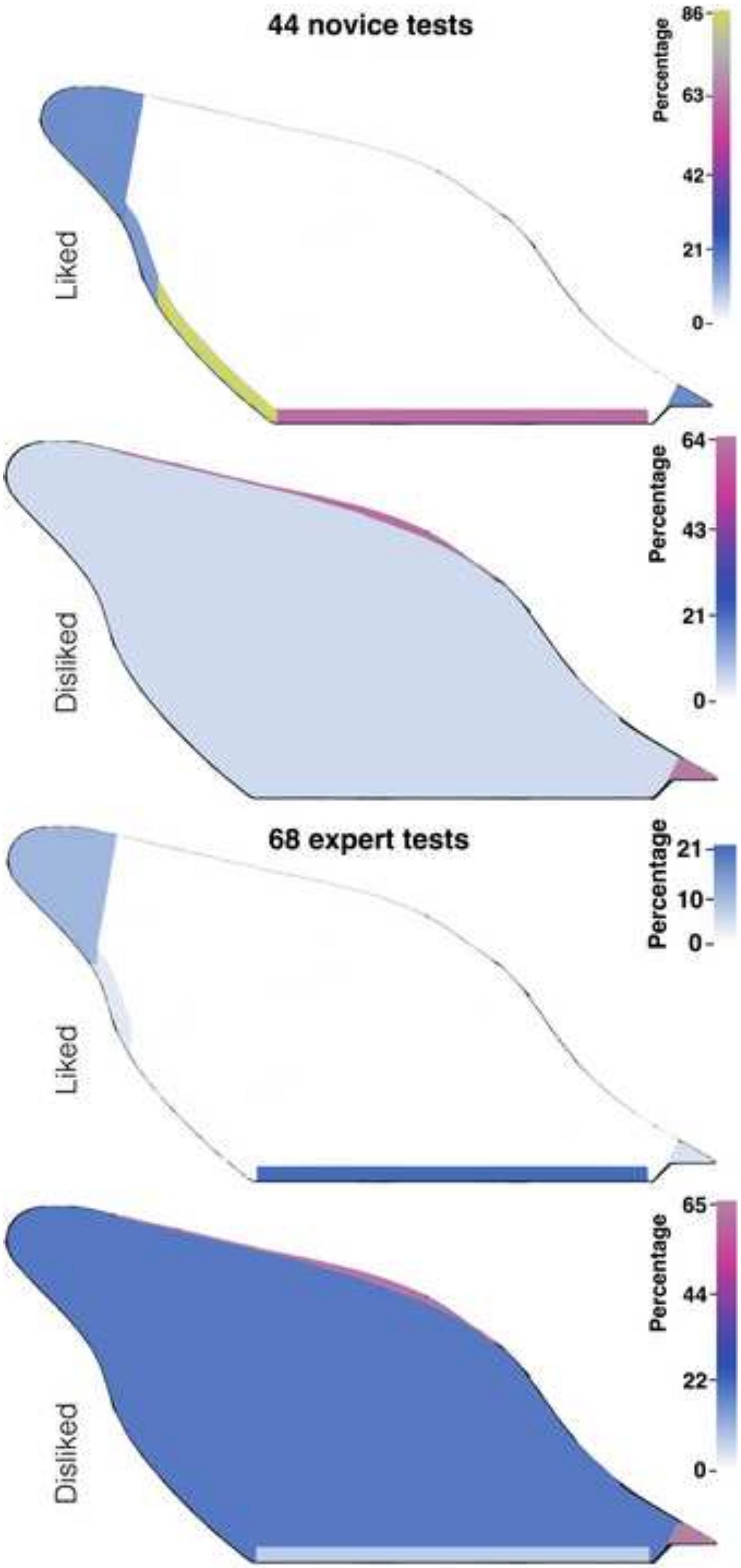

Figure 10

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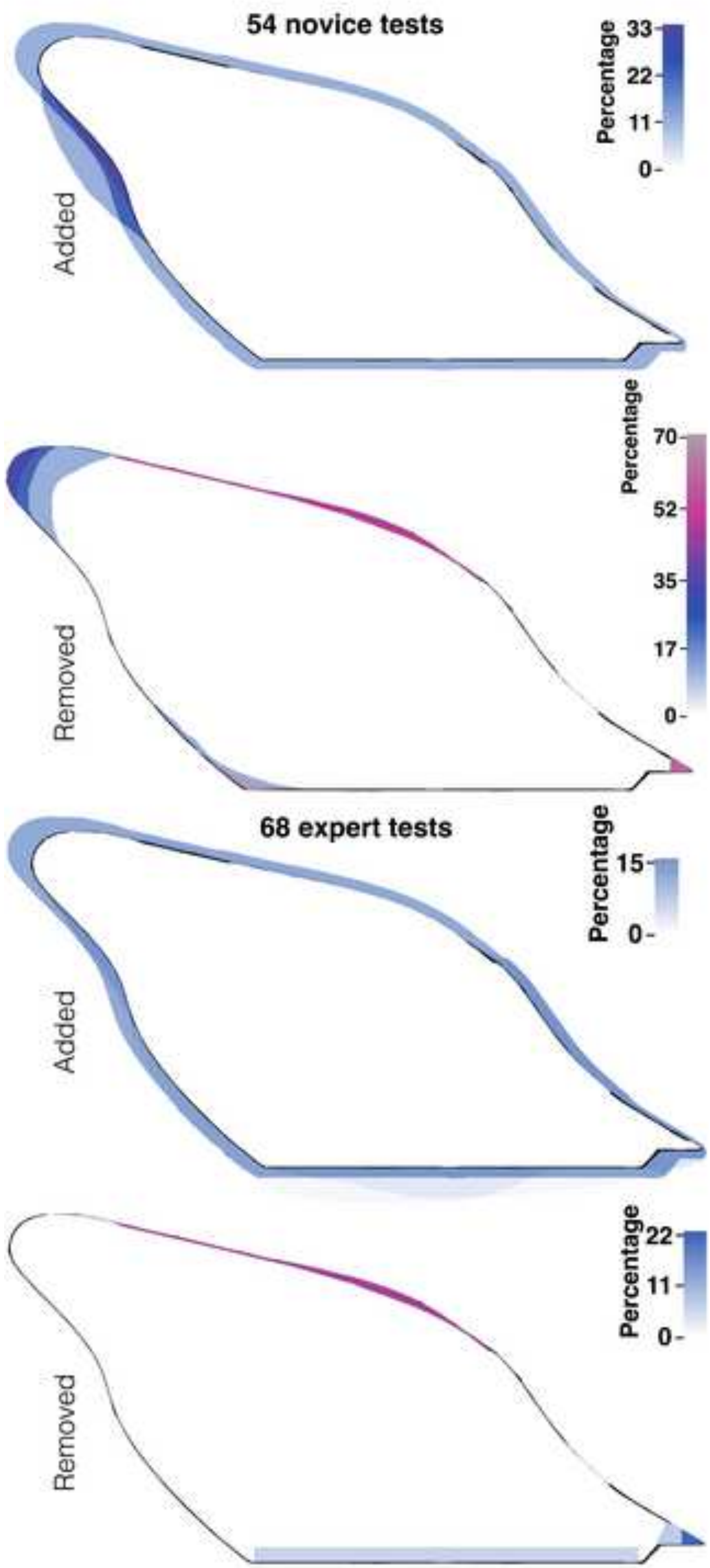

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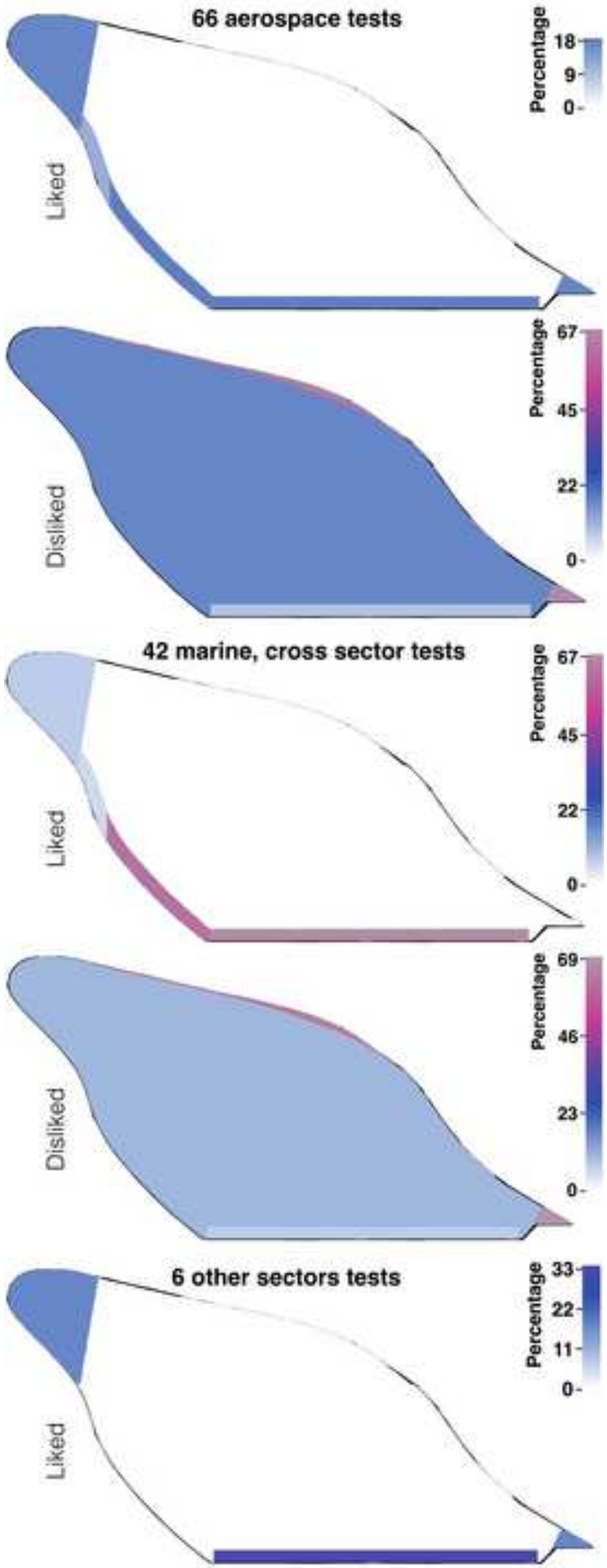

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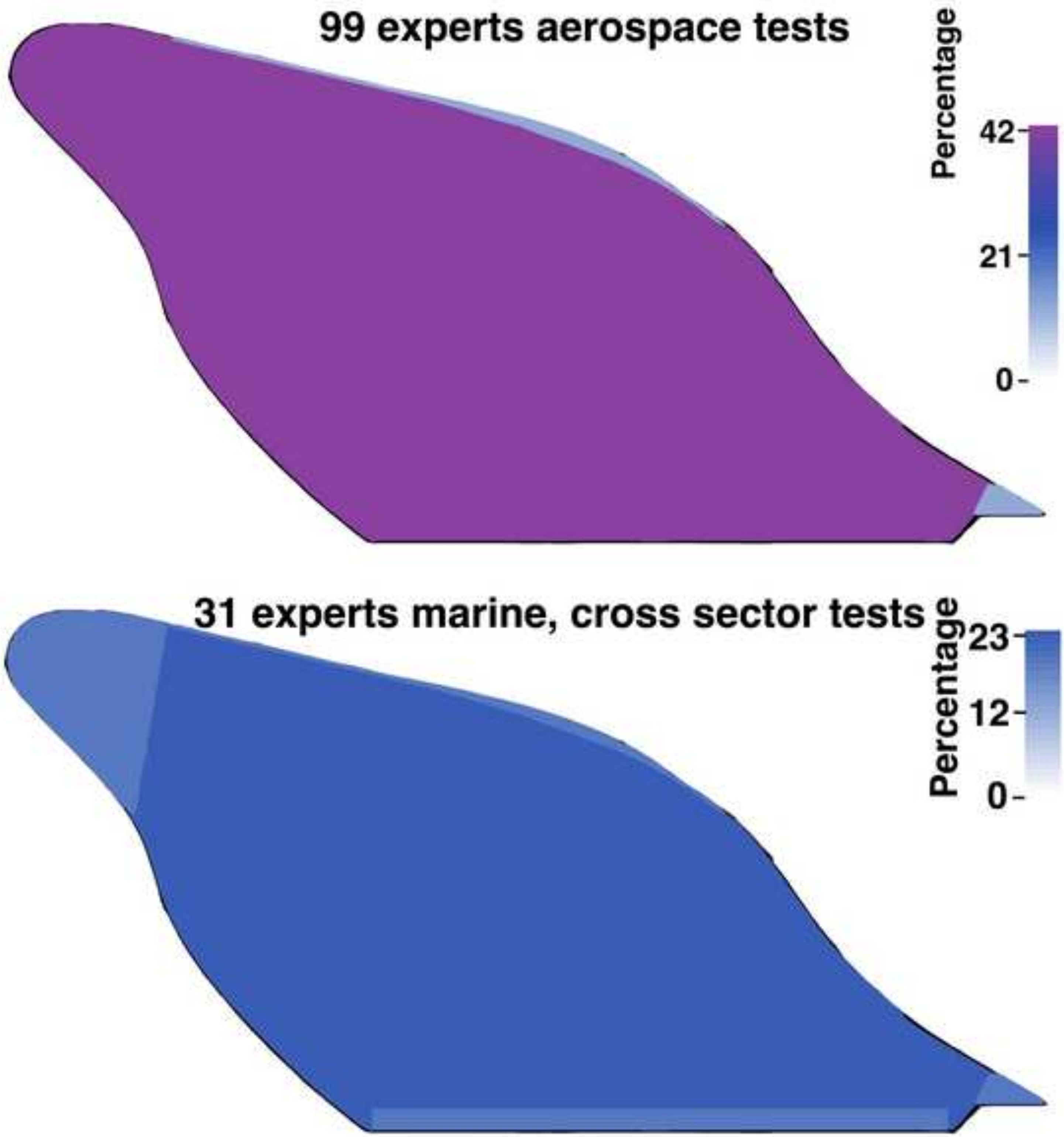


Table 1

	Observations' Details			Participants' Details		
Observation	**Where Observed**	**Sector**	**Context**	**No.**	**Experience**	**Gender**
1	Laboratory environment	Cross sector	Individual: conversations and observations were with a participant working alone	1	Over 20 years	Male
2	Production environment	Cross sector	Individual and Group: conversations and observations were with participants both working together and alone	3	Novice to 14 years	All Male
3	Production environment	Marine	Individual and Group: conversations and observations were with participants both working together and alone	4	Up to 16 years	All Male
4	Production environment	Aerospace	Individual: conversations and observations were with a participants working alone	8	Novice to 10 years	7 Male and 1 Female

Table 2

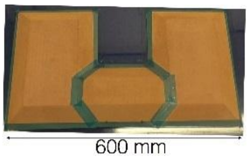
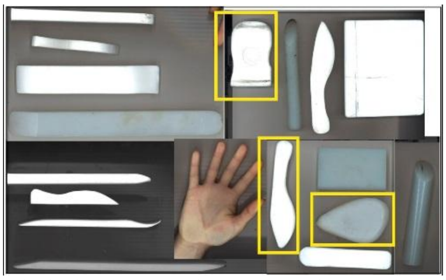
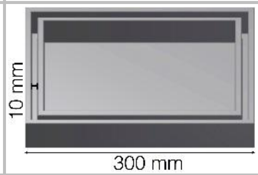
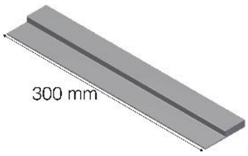
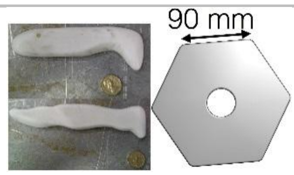
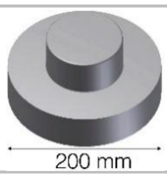
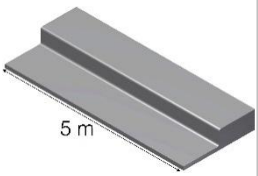
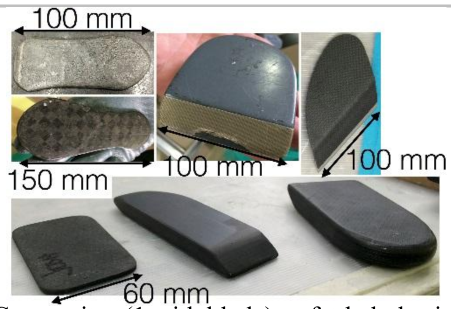
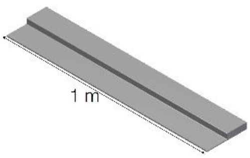
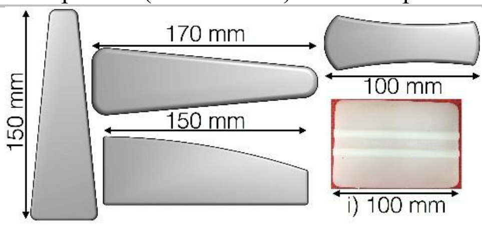
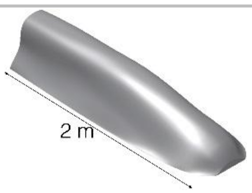
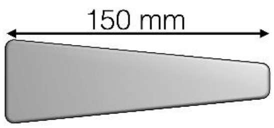
Observation	Feature on Mould Geometry	Challenges with Part	Tools Observed and Discussed	Challenges with Tool
1: An individual participant in a laboratory		Size of internal features smaller than hands	 Fettled plastic, mostly PTFE. Observed tools highlighted with yellow box.	Differences in tool geometry reflect the requirements of mould geometries. Tools are made from different materials and have different weights because of the material that could be sourced.
2: An individual participant in prodution		Size of internal features smaller than hands	 Metal spatula with composite grip	Needs to be fine but the spatula is sharp and risks damaging the part.
2: A group of participants in prodution		Size of internal features smaller than hands	 Fettled PTFE	Different tools for similar mould geometries. The tool geometry depends on the laminator
3: An individual participant in production		Size of internal features smaller than hands	 Adapted metal blade attached to handle	Needs to be finer than what the laminator can make with their hands.
3: An individual and a group of participants in production		Scale of part needs more than one laminator to handle a ply. To form heavy plies requires a higher force than the laminator can exert with their hands.	 Composites (1 with blade) or fettled plastic	Different tools for similar mould geometries. The tool's material and geometry depends on the laminator's previous experience, the prepreg and scale of mould geometry.
4: Individual participants in production		Size of internal features smaller than hands	 Fettled plastic, mainly HDPE. i) Injection moulded HDPE	Tool (i) does not allow access to tight internal corners or the exertion of higher forces. The fettled tools do not allow for controllable production.
4: Individual participants in production	 Represents scale and types of curvature	Scale of part requires laminators to climb on it, leading to problems with posture and back ache.	 Fettled HDPE or the laminators use a piece of plastic/paper to smooth plies.	The fettled tools do not allow for controllable production.

Table 3

Prototype	Materials
1	Polylatic acid, rubber with surface texture and clay
2	Acrylic and latex
3	Acrylic and rubber with surface texture
4	Polylatic acid, rubber and clay
5	Hard and deformable plastic card
6	Rubber
7	Rubber with surface texture
8	Syntatic foam, neoprene and foam
9	Silicone, neoprene and clay
10	Syntatic foam and silicone coated Kevlar
11	Leather, Rhenoflex and Thermomorph
12	Silicone and neoprene

Table 4

Prototype		Mould Geometry				
		Flat Surface	Tight Internal Edge	Rounded Internal Edge	Tight External Edge	Rounded External Edge
1	Advantages		Geometry Matching	-	-	-
	Challenges	Geometry Matching	Comfort	-	-	-
2	Advantages	-			Comfort	Comfort
	Challenges	-	Geometry Matching, Material	Geometry Matching, Material		
3	Advantages	-	-	-	-	Material
4	Advantages	Geometry Matching, Material, Standardised Approach	Material	-	-	-
	Challenges	Comfort	Comfort	-	-	-
5	Advantages	Material, Comfort, Geometry Matching	Material, Comfort	Material, Comfort	-	Material, Comfort, Standardised Approach
	Challenges		Geometry Matching	Geometry Matching	-	Geometry Matching
6	Advantages	Comfort	Material, Comfort	Material, Comfort	Material, Comfort	Material, Comfort
	Challenges	Material	Geometry Matching, Material	Geometry Matching, Material	Material	Material
7	Advantages	Comfort, Standardised Approach	Material, Comfort	Material, Comfort	-	Standardised Approach
	Challenges		Geometry Matching	Geometry Matching	-	
8	Advantages	Comfort	Comfort	Comfort	-	-
	Challenges	Material	Geometry Matching, Material	Geometry Matching, Material	-	-
9	Advantages	Comfort	Comfort, Standardised Approach	Comfort, Standardised Approach	Standardised Approach	Standardised Approach
	Challenges	Material	Geometry Matching	Geometry Matching	Comfort	Comfort
10	Challenges	-	Comfort	-	-	-
11	Advantages	Standardised Approach	Standardised Approach	-	-	-
	Challenges	Comfort		-	-	-
12	Challenges	Comfort	-	Comfort, Material	-	-

Table 5

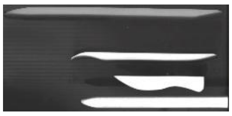
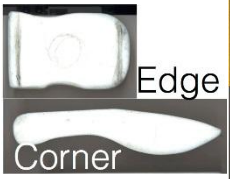
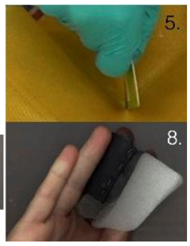
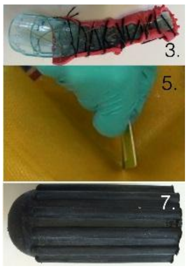
Feature on Mould Geometry	Why the Hand is Not Suitable	Why the Hand is Suitable	Typical Manufacturing Tool	Typical Prototype	Tool's Requirements
Internal feature (approx. 10 mm wide)	Not geometry matched, finger is too big				Geometry matching
Deep, large internal feature (with internal details)	Not geometry matched, arm not long enough				Geometry matching
Internal edge or corner (RoC 3 mm – 30 mm)	Not geometry matched, individual nature of hands Comfort, issues with fatigue and gloves sticking to plies	Fingertips combine sensing with compliance and stiffness			Geometry matching – narrow flat edge and corner Comfort – the tool can be used with ease Material – doesn't stick to the plies and allows the tool to be gripped with ease
External edge or corner (RoC 3 mm – 30 mm)	Comfort, issues with fatigue and gloves sticking to plies	Fingertips manipulate and consolidate the plies whilst conforming to a wide range of curvatures			Comfort - use of deformable material to make lay-up easier Material – doesn't stick to the plies
Flat surface	Comfort, issues with fatigue and gloves sticking to plies	Grouped fingertips (horizontal surface) or side of finger (inclined surface) are a large adaptable surface for smoothing			Geometry matching – an edge with a length longer than the hands Comfort – the tool can be used with ease Material – doesn't stick to the plies and allows the tool to be gripped with ease
Large double curvature (approx. RoC 150 mm, approx. length 2 m)	Not geometry matched, hands are not large enough Comfort, challenge to manipulate plies larger than the body and issues with gloves sticking to plies	Hands conform to a wide range of curvatures	Piece of plastic to cover the hand		Comfort - use of deformable material to make lay-up easier Material – doesn't stick to the plies Geometry Matching – larger than the hands

Table 6

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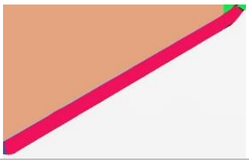
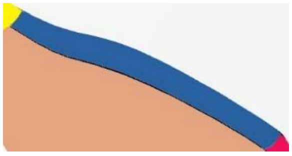
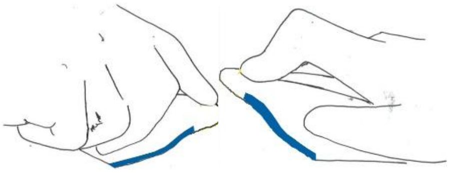
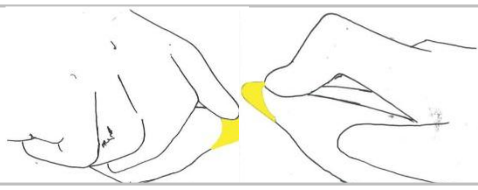
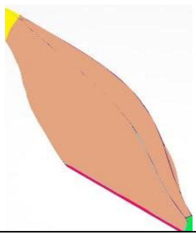
	On how they used the Dibber			On how they modified the Dibber		
	Aerospace	Marine, Cross sector	Other sectors	Aerospace	Marine, Cross sector	Other sectors
Expert	49	15	6	50	16	3
Novice	44	27		28	26	

Table 7

Form of Tool's Feature	Feature's Taxonomy		
	Mould Geometry Where Feature Used	**Requirement this Feature Meets**	**Picture to Describe Grip to Use Feature on Tool**
Point 	Corner on internal mould geometry	Geometry matching	
Long flat edge 	Flat surface or straight edge on internal mould geometry	Geometry matching	
Curved flat edge 	Curved internal mould geometry	Geometry matching and comfort	
Rounded edge 	Curved or inclined straight edge on internal mould geometry	Geometry matching and comfort	
Grip 	-	Comfort	-