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A design framework for the mass customisation of custom-fit bicycle helmet models

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ABSTRACT

Mass customisation (MC) can provide significant benefits to the customers. For example, custom-fit design approaches can improve the users' perceived comfort of products where the fit is an important feature. MC can also bring major value to the producers, where for instance, premium prices can be implemented to the products. Research show that MC can bring competitive advantages especially when the system is new. It is therefore surprising that MC of helmets has not been studied more extensively, especially given the advances in 3D scanning, computational analyses, parametric design, and additive manufacturing techniques. The purpose of this study was to present a novel MC framework for the design of custom-fit bicycle helmet models.

In the proposed design framework, we first categorized a subset of the Australian population into four groups of individuals based on their similar head shapes. New customers were then classified inside one of these groups. The customisation took place inside these groups to ensure that only small variations of the helmet liner were implemented. During the design process, the inside surfaces of a generic helmet model was modified to match the customer's head shape. We demonstrated that all the customized models created complied with the relevant drop impact test standard if their liner thickness was between the worst and best case helmets of each group. Fit accuracy was verified using an objective evaluation method. Future work should include detailed description of the manufacturing methods engaged in our MC framework.

1. Introduction

Mass customisation (MC) aims at providing customised products or services to consumers in large volumes and at costs reasonably low compared to conventional customisation processes (Davis, 1989; Pine, 1993; Da Silveira et al., 2001). More specifically, MC systems seek to reach customers as in the mass produce market but try to consider them individually as in the on-one production method. The reasoning behind the growth of MC systems in the late 1980s, early 1990s was threefold; (i) the development of advanced manufacturing technologies, (ii) the increased demand for diversity in the products' range and, (iii) the collapse of many mass industries (Pine, 1993; Hart, 1995; Kotha, 1995), all increasing the need of production methods focusing further on the individual.

As summarised by Da Silveira and co-authors in the well documented MC reviews in (Da Silveira et al., 2001) and (Fogliatto et al., 2012), multi degrees of mass customisation exist, from full customer product specifications, to simple options selection. Although a fully individualisation (e.g. bespoke tailoring) can hold more value to the consumer, often compromises must be reached to an acceptable level of customisation for a specific product. Therefore, MC should be a good mix between standardisation and individualisation to be successful (Westbrook and Williamson, 1993).

Multiple generic levels of mass customisation have been proposed in the past (Pine, 1993; Lampel and Mintzberg, 1996; Gilmore and Pine, 1997; Spira, 1993). Da Silveira et al (Da Silveira et al., 2001). condensed the proposed classifications in an eight-level MC scheme, ranging from whole customisation (consumer create the product in collaboration with the designer) to whole standardisation. MC products between these two extreme categories might be individualised at either the fabrication level (customer-

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tailored products), the assembly level (modular components), the delivery level (simple addition), the distribution level (different packaging), or the usage level (customers can alter the product during use). Evaluating the appropriate level of individualisation for a specific product can be difficult. Ideally, preliminary studies should assess the customers' interest to a level of customisation, measure the feasibility to deliver at this level, and determine if achieving such level holds comparative advantages.

In this paper, we present a MC framework for the design of custom-fit bicycle helmets. Custom-fit meaning personalised in respect of shape and size. A custom-fit bicycle helmet, designed based on the individual's head shape, is expected to improve fit and comfort of the bicycle helmet. Even though the most important function in wearing a bicycle helmet is to provide head protection to the cyclist in the event of an accident, numerous surveys from the literature have indicated wearing a helmet is not comfortable and the current sizing of helmet does not provide a good fit for the users (Kotha, 1995; Fogliatto et al., 2012; Westbrook and Williamson, 1993; Lampel and Mintzberg, 1996). The leading reason for this helmet discomfort is that the human head shape and dimensions are different according to ethnic background, age and gender (Pine, 1993; Da Silveira et al., 2001; Hart, 1995). It was also reported that Asian users experience poor fit because most helmets currently available on the market are designed according to the size of Western heads (Da Silveira et al., 2001; Gilmore and Pine, 1997). Therefore, based on these helmet fit problems reported in the literature, we could conclude that the users are not satisfied with the current general size of the bicycle helmet and it does not provide the best selection of sizing to improve the helmet fit, comfort and ergonomic. In addition, the discomfort of a product, in this case, due to the helmet fit, is also one of the customer's sacrifices gap (Hart and C.W., 1995). The bigger the gap would also drive the need of customisation of a product (Gilmore and Pine, 1997; Hart and C.W., 1995; Rogers and Peppers, 1993; Whiteley and Hessan, 1996). Other examples of the sacrifices gaps are such as hassle, inconvenience, long queues, product deficiencies, high cost and ordering difficulties (Hart and C.W., 1995). A potential solution to overcome the helmet fit problem for each individual is the mass-customisation helmet design approach, where the helmet liner is designed according to the size and shape of the head of the individual. This approach could improve the helmet fit and comfort, and at the same time satisfy all head shape, regardless of age, gender and ethnic background. However, there have been only limited studies addressing the mass customisation framework of bicycle helmet. Most previous studies in the literature focused on the materials used for the liner, such as Functionally Graded Foam Liner (FGF) (Thai et al., 2015a), the dual-material combination of two polyurethane foams (Thai et al., 2015b), and Aluminium honeycomb (ALH) (Ellena et al., 2016), and their influence on the impact performance of the helmet. Other studies have also described new helmet liner designs, such as the liner design using deformable cones made from Acrylonitrile Butadiene Styrene (ABS), which was proposed by Blanco et al. (Fiore et al., 2003).

In this work, we built our MC framework around the *transparent* principle (Gilmore and Pine, 1997), where products are almost fully altered to match the needs of each individual (i.e. need for well fitted helmets). However, we keep a modular approach in our design process where only the inside foam liner of a standard helmet model is altered to fit the customer's head shape and size. In the following section, we justify the need for custom-fit helmet models by addressing the two market-related factors identified in the literature for successful implementation of MC systems (Da Silveira et al., 2001; Fogliatto et al., 2012).

Customer demand for customisation must exist. Customers must appreciate the added value of MC products to initiate demands. Merle et al. (2008, 2010). investigated further the works from (Addis and Holbrook, 2001; Squire et al., 2004) to identify the drivers of MC value from the consumers' perspectives. They demonstrated that the perceived value increases as a result of the intrinsic and extrinsic characteristics of customised products. On the one hand, the utilitarian value (obtaining a product which matches one's preferences the closest), the uniqueness value (distinguishing oneself from others via the mass-customised product) and the self-expressiveness value (obtaining a product that represents oneself) are great benefits conveyed by MC systems. On the other hand, what seems most important is the experience provided, which was defined as the hedonic value (pleasure, fun, inspiration and excitement felt during the MC experience), and the creative fulfilment value (accomplishment related to the creative task of co-designing).

The need for better-fitted helmets has been highlighted in the literature since the 1990s (Robinette and Whitestone, 1994). However, little improvements have been reported for helmets in terms of fit (Thai et al., 2015a, 2015b; Ellena et al., 2016). In our MC approach, a generic bicycle helmet model is automatically redesigned to fit the customer's head shape. Consequently, the new liner will improve the user's perceived comfort and will add product value in terms of uniqueness and hedonic values. Furthermore, as pointed out by Fiore et al. (2003), the use of 3D body scanning can contribute to added benefits and may increase the customers' willingness to take part in mass customised products.

Market conditions must be appropriate. MC can offer significant competitive advantages over competitors, especially when the system is original (Kotha, 1995). From a producer's perspective, value is added by premium prices for mass customised products, increased customer loyalty and improved brand reputation (Piller et al., 2004). All of which could bring significant market shares to manufacturers, who are willing to embark on the MC production method.

While individualisation in the garment industry is now recognised has a valuable alternative to standardisation (Otieno et al., 2007; Song and Ashdown, 2012; Lim, 2009), very scarce works on helmet customisation has been either reported in the literature or initiated by industries. Lui et al (Liu et al., 2008). first attempted to design custom-fit helmets using a semi-parametric surface modelling tool and 1D anthropometric data (e.g. head circumference, head breath, and head length). Their helmets were fabricated from only a hard shell (no foam liner), with a simple rounded egg-shape that offers limited design features. These helmets can be designed as simple parametric models with just a handful of parameters. Conversely, contemporary bicycle helmets have complex free-form shapes with ventilation holes that require advanced design models. Pandremenos and Chryssolouris (2009) created a custom-fit motorcycle helmet liner (again a simple rounded egg-shape design) using a modular design approach and rapid manufacturing technologies. Although the method proposed could be applicable to many different customised products other than helmets, 3D printing the liner using polyurethane will greatly alter the shock absorption properties of the helmet. This issue was not addressed by the researchers. In 2013, Bell Sports® (Rantoul, Illinois, USA) launched a Custom-Fit program for two of their motorcycle helmet models. Based on a 3D scan of the user's head, Bell Sports® claimed that the Expanded Polystyrene (EPS) liner is individually redesigned to fill the void between the head shape and the shell.

Safety standards and certification may be one of the main reasons for the lack of MC systems of helmets. According to international and national standards, helmets are to be tested on a range of standard mannequin heads called headforms. They aim to