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Development of Silicone Elastomer for Use in the Assessment of Padded Clothing in Rugby Union †

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† Presented at the 13th conference of the International Sports Engineering Association, Online, 22–26 June 2020.

Published: 15 June 2020

Abstract: Rugby Union is a collision sport, with both player to player and player to pitch impacts being frequent. Current test standards for padded clothing in rugby use impact surrogates, which may not accurately replicate the human response. Modern technologies use silicone elastomers to represent human soft tissue when testing padding, however many commercially available silicones do not match the load response seen by human tissue. This paper describes the fabrication and validation of a bespoke formulation of commercially available silicone elastomer and deadener concentrations that portray a similar load response to relaxed organic muscle tissue. The mechanical responses, both at quasi-static and dynamic strain rates, have been compared, with improved, more representative behaviour being presented. The validation of this silicone elastomer formulation is important in developing a more biofidelic impact surrogate for the assessment of padded clothing in rugby.

Keywords: Rugby Union; human tissue simulant; muscle; silicone; padded clothing; injury prevention; impact testing

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1. Introduction

Sports injury biomechanics research attempts to reduce injury to athletes, through the understanding of both human responses to appropriate ‘real life’ loading conditions and the mechanisms of injury. Human surrogates are used in injury biomechanics research to provide a representation of the living human so that these mechanisms can be understood without the need for human or animal experiments. Human surrogates are frequently used in the automotive, defense and medical industries, however less frequently in sports injury biomechanics research. Their most common function is in impact testing in order to evaluate the effectiveness of injury-preventative measures. In Rugby Union, padded clothing, commonly known as shoulder padding, is worn to dissipate the impact force experienced at the shoulder in a collision. Shoulder pads are a common item of a player’s dress, with Rugby Union matches averaging 463 contact events per game and average tackle forces being 3400 N [1,2]. World Rugby identifies padded clothing to not be a form of protection. Current test standards for padded clothing are designed to minimise their protective properties so that they do not negatively affect the game of Rugby Union as we know it, however the injury-preventative capabilities of shoulder padding are relatively unexplored. Coupled with this, testing standards for padded clothing use unrepresentative human surrogates (rigid metal anvils) for the padding to be placed upon for impact testing [3]. This presents an opportunity to develop a more biofidelic impact test to better asses the performance of padded clothing in Rugby Union.

Silicone elastomers have been used in past research to represent human tissue structure because of their similarities in density (approximately 1000 kg·m^{-3}) and load response, as well as their ease of use, durability and consistency [4]. Past research has employed commercially available silicones as a human tissue simulant, with Hrysomallis using Silastic 3481 to replicate a human thigh in sports Personal Protective Equipment (PPE) research [5]. However, more recent research by Payne found that Silastic 3481's behaviour is stiffer than that of relaxed organic tissue data [4]. This is possibly because the silicone was used to match muscle, adipose and skin structures, without taking into account their differences in mechanical response and layer interactions. The addition of silicone deadener can be used to decrease the stiffness of silicones by inhibiting crosslinking of polymer chains at the curing stage [6]. Therefore, through an iterative process, similar mechanical properties to relaxed organic tissue can be achieved. Validation commonly uses porcine tissue data as opposed to human tissue data because of the ethical and practical implications, as well as their mechanical similarities [7]. Tissue data is tested ex vivo, meaning a lack of tissue tension is exhibited in testing, however ex vivo data gives current best estimates of the mechanical response of relaxed human tissue. Very few studies have looked to characterise the quasi-static and dynamic compressive response of organic muscle tissue. Song et al. explored the effect of strain rate on porcine muscles' compressive response [8]. Strain rates varied from 0.007 s^{-1} to 3700 s^{-1} with a stiffer response being seen at higher strain rates. Song highlighted the effect of sample preparation and testing conditions on results. Obtaining original well-explained porcine tissue data to validate silicone formulations would therefore be beneficial.

Ensuring silicone elastomer formulations display a similar mechanical response to human tissue is important in developing a more biofidelic impact surrogate for the assessment of padded clothing in rugby. Therefore, the aim of this study was to develop a silicone elastomer formulation that presents a similar load response, at both quasi-static and dynamic strain rates, to relaxed organic tissue.

2. Materials and Methods

2.1. Material Preparation and Fabrication

Due to its prior use in impact surrogate research and its commercial availability [5], Silastic 3481 was used as a starting point for this study. Payne [4] found that Silastic 3481 was stiffer than relaxed organic muscle tissue; to overcome this issue a three-part blend with the addition of a catalyst and deadener was formulated. An iterative development process found a 10:1:4 (base: catalyst: deadener) weight ratio constitution most closely matched the compressive stress-strain properties of relaxed organic tissue. The blend was thoroughly mixed and fully degassed before being poured into American Society for Testing and Materials (ASTM) D395 (29 mm Ø, 12.5 mm height) cylindrical test moulds for quasi-static compressive testing as seen in Figure 1 and cubic (7 mm width, 7 mm length, 12.5 mm height) test moulds for dynamic mechanical analysis. Test specimens were left at room temperature for 7 days before removing from their moulds to fully cure. The same process was followed with control samples of Siliastic 3481 plus catalyst in a 10:1 (Base: Catalyst) weight ratio. Deceased organic porcine shoulder muscle tissue was taken from a 2 year old pig slaughtered 2 days before testing. The porcine muscle tissue was cut using bespoke stamps to cylindrical test specimens (29 mm Ø, 12.5 mm height) for quasi-static testing and cubic test specimens (7 mm width, 7 mm length, 12.5 mm height) for dynamic mechanical analysis. All test specimens were measured using digital calipers (Mitutoyo, Takatsu-ku, Japan) to ensure the correct shape and size was obeyed.

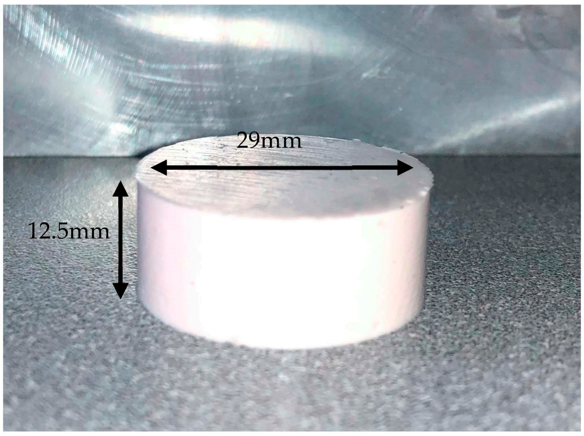

Figure 1. ATSM D395 Silicone test sample.

2.2. Quasi-Static Compressive Material Characterisation

The cylindrical test moulds were coated in vaseline prior to testing to reduce friction. A Shimadzu test machine (Shimadzu, EZ-LX, Kyoto, Japan) was used to measure the compressive response of the silicone elastomer and porcine samples. A compressive test protocol was used increasing the engineering strain at a strain rate of 0.067 s^{-1} until material failure was achieved. This was repeated for 5 different test specimens of the silicone elastomer and porcine muscle and a median result was taken. Force, displacement and time outputs were taken from the test machine in order to calculate engineering stress and strain.

2.3. Dynamic Mechanical Analysis

The cubic test molds were placed in a Dynamic Mechanical Analyser (Metravib, VA2000, Limonest, France) to characterise the compressive response at a dynamic strain rate. To observe the effects of dynamic strain on the dynamic mechanical properties of the specimens, a strain sweep from 0% to 1% was performed at 10 Hz at room temperature. The compressive young's modulus was recorded in order to ensure the silicone elastomer represented a similar mechanical response to porcine muscle tissue.

3. Results

3.1. Quasi-Static Compressive Material Characterisation

Figure 2 displays quasi-static stress-strain compression plots for porcine muscle tissue, Silastic 3481 and Silastic 3481 plus deadener, in a 10:1:4 weight ratio (Silastic 3481 plus Deadener). The percentage error when compared to the porcine muscle data is plotted alongside to represent the differences observed. The results show a clear significant difference between the porcine muscle tissue data and the Silastic 3481. The Silastic 3481 plus deadener specimen displays a far closer match to that of the porcine muscle data. There are still differences at lower strains which should be explored further.

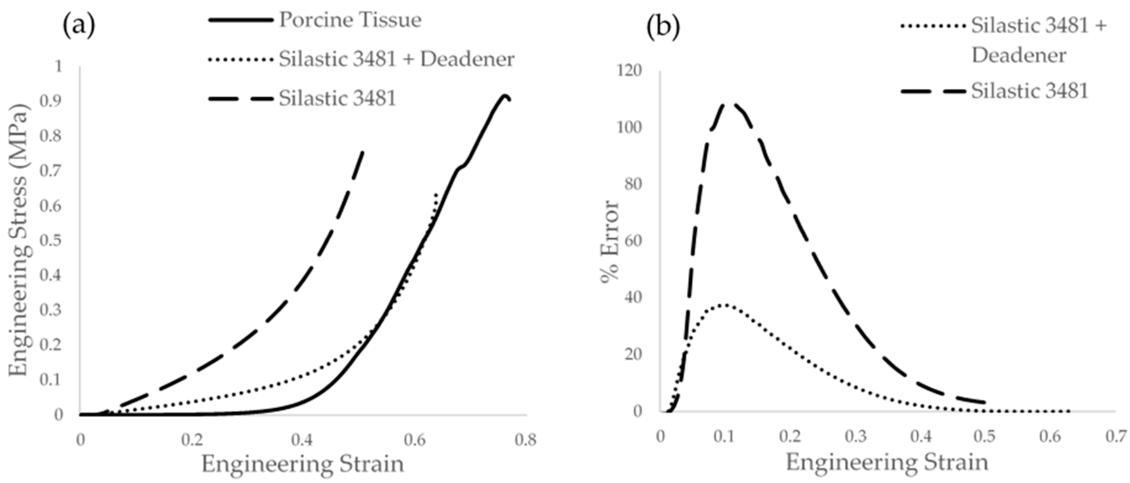

Figure 2. (**a**) Compressive stress-strain plot comparing porcine muscle, Silastic 3481 and Silastic 3481 plus Deadener; (**b**) Percentage difference of Silastic 3481 and Silastic 3481 plus Deadener compared to porcine muscle.

3.2. Dynamic Mechanical Analysis

Figure 3 displays the dynamic strain against the compressive Young's modulus of experimental porcine muscle tissue data, Silastic 3481 and Silastic 3481 plus Deadener. The results show a clear significant difference between the porcine muscle tissue data and Silastic 3481. The Silastic 3481 plus deadener specimen displays a far closer match to that of the porcine muscle tissue data. The Silastic 3481 specimen is far stiffer than that of the porcine muscle tissue. This response runs in line with the quasi-static stress-strain results.

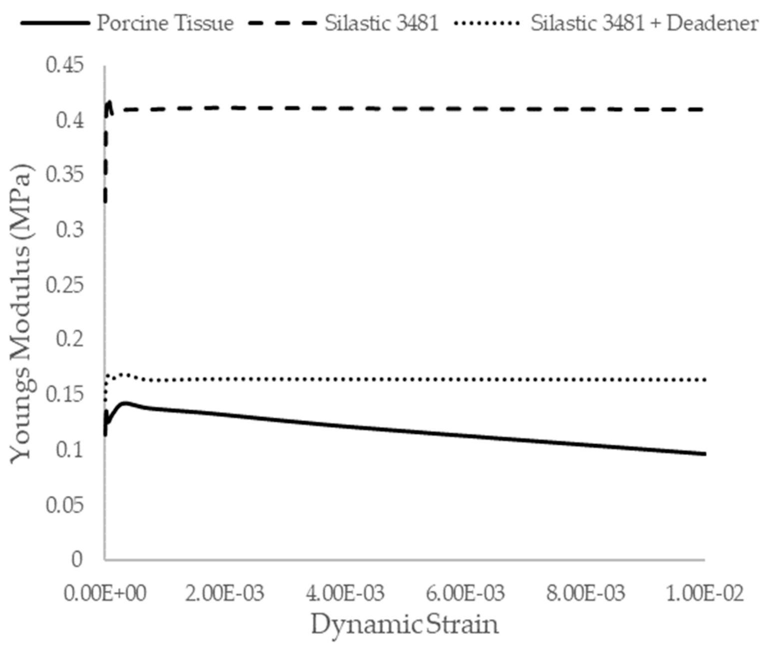

Figure 3. Strain sweep of Young's modulus comparing porcine muscle, Silastic 3481 and Silastic 3481 plus Deadener.

4. Discussion

The study presents the initial stages of the development of a biofidelic impact surrogate for the assessment of padded clothing in Rugby Union. The aim was to develop a silicone formulation with similar mechanical properties to relaxed muscle tissue as this makes up a large amount of the soft tissue in a human shoulder. The Silastic 3481 plus Deadener in a 10:1:4 weight ratio specimen provides a more accurate relaxed muscle tissue simulant than previously used silicone elastomers [5]. Silastic 3481 provides a far stiffer compressive response than that of relaxed porcine muscle. The addition of deadener provided an effective solution to this issue, with results showing the Silastic 3481 plus Deadener specimen having similar stiffness to relaxed porcine muscle. This is because the deadener will inhibit crosslinking of the base and the catalyst, meaning the silicone will not fully cure [9], therefore making the silicone less stiff, giving a more realistic stress-strain response to human tissue [6].

The porcine tissues stress-strain response at a $0.067 \cdot s^{-1}$ provided similar results to previous research by Song et al. [8]. Previous research has highlighted the effect of sample preparation and testing conditions on the mechanical response of organic tissue, and further research into how great this effect is should be explored. The strain rate was much lower than a dynamic rugby impact, although the stress-strain response of human tissue in a rugby impact has not been studied, impact velocity of tackles average 5.6 $m \cdot s^{-1}$ in the tackler and 4.8 $m \cdot s^{-1}$ in the ball carrier [10], whereas the quasi-static strain rate was 0.00083 $m \cdot s^{-1}$ (50 mm/min). Further characterisation of the silicone elastomer's compressive response at more representative velocities should be explored to further validate an impact surrogate.

Although the Silastic 3481 plus Deadener presented a similar stress-strain response to porcine muscle tissue, differences were still seen at lower strains. The porcine muscle's lack of tonicity (muscle tone seen in living organic tissue) means the specimen is less elastic than that of the Silastic 3481 plus Deadener specimen, potentially explaining this response. However, high deformations, and therefore strains, are seen in rugby impacts, making this less of a concern. The effect of muscle contraction on variable stiffness of muscle tissue should also be considered. Both relaxed and contracted muscle behaviour is seen in sports impacts, and how this may affect an impact in rugby must be explored. Studies have explored the effect of muscle contraction [11,12]. However, the effect of muscle contraction on the compressive response of the shoulder is non-existent, possibly due to its complexity.

Silastic 3481 plus Deadener provides a good relaxed muscle tissue simulant. However, the complexity of human tissue means a different response is seen from bone, subcutaneous adipose and skin tissues. The mechanical behaviour of these tissues must be matched, and similar geometries fabricated, in order to develop an impact surrogate that will provide a more accurate impact response. The effect each layer has on the stress-strain response should also be explored, and the thickness and elastic modulus of each layer will greatly affect this [13]. Further research needs to be conducted on the response of organic tissues in more dynamic impact scenarios, but this must be done ex vivo to animal structures due to ethical and practical implications of this research. The development of a rugby impact surrogate is complex, especially with a range of shoulder impacts being presented in the sport. Current technology means the development of an exact impact surrogate is unrealistic, but the approach being taken will lead to a more accurate representation of a shoulder impact in Rugby Union than a rigid striker on rigid anvil impact, which is seen in the current regulation at present. This means the capacity of padded clothing can be more accurately defined.

5. Conclusions

Commercially available silicone elastomers have been used in previous impact surrogate research, however, their mechanical behaviour presents a stiffer response than organic human tissue. Silastic 3481 plus Deadener in a 10:1:4 weight ratio provides a more biofidelic compressive response, at both quasi-static and dynamic loading rates. This could therefore be used to develop a human tissue surrogate for use in the assessment of padded clothing in Rugby Union.

Acknowledgments: This project is funded by World Rugby and the Engineering and Physical Sciences Research Council (EPSRC).

Conflicts of Interest: The authors declare no conflict of interest. The funding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

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