View metadata, citation and similar papers at core.ac.uk

brought to you by CORE

provided by Loughborough University Institutional Repository

Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 72 (2014) 533 – 538

Procedia Engineering

www.elsevier.com/locate/procedia

The 2014 conference of the International Sports Engineering Association

Initial Validation of a Relaxed Human Soft Tissue Simulant for Sports Impact Surrogates

Thomas Payne[a], Séan Mitchell[a]*, Richard Bibb[b], Mark Waters[b]

[a] *Sports Techonology Institute, 1 Oakwood Drive, Loughborough University, Leicestershire, LE11 3QF, UK*
[b] *Loughborough Design School, Loughborough University, Leicestershire, LE11 3TU, UK*
[c] *School of Tissue Engineering & Regenartive Denistry, Health Park, Cardiff University, Cardiff, CF14 4XY, Wales, UK,*

Abstract

Impact injuries are a common occurrence in sport such that personal protective equipment (PPE) is often mandatory to ensure participant safety. Current tests to assess PPE effectiveness often use unrepresentative human surrogates, insufficient to accurately assess human impact response. More refined surrogates typically use “off the shelf” silicone elastomers to better represent human tissue, however using a single simulant material for all soft tissues means some phenomena associated with injury are not adequately represented. This study presents an evaluation of the effectiveness of a bespoke muscular tissue simulant using a proprietary blend of additive cure silicones. The mechanical response has been compared and validated with porcine tissue properties and provides improved behaviour when compared with a previously used silicone elastomer, Silastic 3481. The material has also been modelled computationally using a two-term Ogden model and exhibits a significantly different response to Silastic 3481 under a low-speed knee-strike loading condition.

© 2014 Elsevier Ltd. Open access under CC BY-NC-ND license.
Selection and peer-review under responsibility of the Centre for Sports Engineering Research, Sheffield Hallam University

Keywords: Sports; surrogate; impact; muscle; simulant; silicone; additive cure; PPE; FEA

* Corresponding author. Tel.: +44(0)1509 564804; fax: +44(0)1509 564801.
E-mail address: s.r.mitchell@lboro.ac.uk

1877-7058 © 2014 Elsevier Ltd. Open access under CC BY-NC-ND license.
Selection and peer-review under responsibility of the Centre for Sports Engineering Research, Sheffield Hallam University
doi:10.1016/j.proeng.2014.06.092

1. Introduction

Impact injuries in sports are a common occurrence which not only restrict participation in future physical activity but also place a burden on society in terms of the number of days absent from the workplace. These impacts can result in injuries ranging in severity from mild muscular contusions and lacerations to complete skeletal fractures. In many sports personal protective equipment (PPE) is mandatory with function and form governed by safety standards prescribing the minimum impact protection performance levels.

Current test standards typically use unrepresentative human surrogate targets (e.g. simple metal anvils) to 'wear' the PPE. The development of more sophisticated biofidelic surrogates presents the opportunity to better assess the effectiveness of PPE by more closely simulating injurious tissue behaviour to demonstrate the efficacy of protective interventions. A key requirement for PPE test surrogate materials is that they behave consistently and are either inexpensive (for frangible single use) or durable (for repeat use) so that accurate assessments can be made within and between PPE samples (Payne et al., 2013).

Silicones are commonly utilised as soft tissue simulants due to their consistency, durability and comparable tissue density (approximately 1000kg.m^{-3}). Typically surrogates tend to use specific off the shelf silicones to represent all tissue structures in the target body segment (Roberts et al., 2007; Petrone et al., 2010); Silastic 3481 was used by Hrysomallis (2009) and has since been employed elsewhere within the sports PPE industry.

Figure 1 shows the response of a range of key organic structural tissues in comparison with Silastic 3481 when subject to quasi-static compressive mechanical loading. The tissues are all tested *ex vivo* and as such lack a resting muscular tonicity. Given practical and ethical limitations associated with human tissue testing, cadaver tests provide an indication of current best estimates of relaxed organic tissue behaviour. Data shown for subcutaneous adipose tissue and muscle are taken from tests on porcine tissue whilst skin data were adapted from tests on human tissue. Porcine tissue offers a more abundant source of mechanical property data and possesses a structure biologically similar to humans (Shergold et al., 2006); although it has been suggested that porcine tissue contains a greater concentration of collagen fibres and as such may behave stiffer when subject to comparable loading. The graph shows Silastic 3481 does not provide a good match with any single organic tissue.

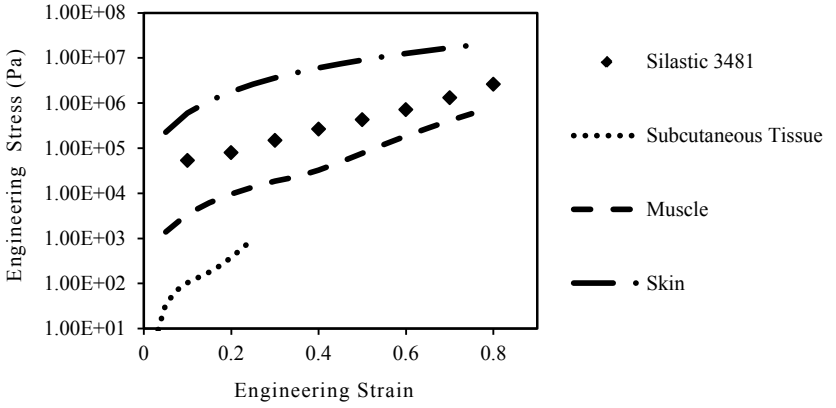

Figure 1 - Stress-strain plot of quasi-static compressive response of Silastic 3481 when compared to skin (Ni'Annaidh et al., 2012), muscle (Song, 2007; McElhaney 1966), and subcutaneous tissue (Comley & Fleck, 2009)

There are many issues and mechanical response phenomena that are ignored through use of a single material surrogate (e.g. relative movement between structures, pressure distribution and deformation of tissues distant from the impact site). Superior biofidelity to simulate these can be achieved by developing surrogate materials for each human tissue type. This paper presents research evaluating the mechanical properties of a potentially improved relaxed muscle simulant.

2. Method

2.1. Materials Fabrication

A propriety blend of two-part additive cure Polydimethylsiloxane (PDMS) silicone elastomer was formulated through variation of polymer, catalyst and cross-linker constituents. An iterative development process was undertaken altering polymer and cross-linker concentrations to attain an elastomer more closely matching organic tissue properties. Formulated silicone constituents were thoroughly mixed and placed in a vacuum chamber until fully degassed. The solution was then cold poured into ASTM D395 cylindrical compressive specimen moulds (29mm Ø, 12.5mm height) and placed in an environmental chamber at 90^{o}C to fully cure. Silastic 3481 samples were prepared in a similar manner using a 10:1 Part A:B ratio concentration.

2.2. Test Protocol

The compressive test samples were removed from the mould and cleaned to remove any contaminants. The ends were coated in Vaseline to reduce friction and ensure the measured response is predominantly due to axial compressive loading. Tests were conducted using an Instron 5569 universal screw-driven test machine to characterise the mechanical response. A uniaxial compressive test protocol was employed increasing the engineering strain at a quasi-static loading rate of 0.4s^{-1} until material failure was achieved. Force, displacement and time outputs were obtained from the test machine and used to calculate engineering stress and strain parameters.

2.3. Sports Impact Modelling

A Finite Element Analysis (FEA) model was developed using Abaqus Explicit solver to compare the anticipated behaviour of the new surrogate material with predicted Silastic 3481 and organic tissue responses in an intermediate strain rate sports relevant impact. A knee-on-thigh impact similar to that which may be commonly experienced in sports such as rugby, basketball or martial arts was approximated with a 75mm diameter spherical striker (mass 2.8kg, velocity 2ms^{-1}) as proposed by Halkon et al. (2014).

The surrogate muscle structure was approximated by a 50mm thick, 200mm diameter cylindrical puck constrained rigidly at its base with an encastre boundary condition struck centrally and perpendicular to the flat surface by the impactor. 32682 hexagonal elements were used in the surrogate (approximate element size: 3.5mm) with enhanced hourglass control and a distortion control length ratio of 0.3 to prevent element distortion in the hyperelastic material. A surface-to-surface contact interaction between the interfacing surfaces was employed with a hard normal contact and tangential penalty contact with a frictional coefficient of 0.25.

3. Results

3.1. Uniaxial Compressive Materials Characterisation

Figure 2 presents quasi-static stress-strain curves from uniaxial tests conducted on both the developed PDMS silicone, Silastic 3481 and reference porcine muscular tissue data (McElhaney, 1966; Song et al., 2007). The percentage error (synthetic vs. organic tissues) is plotted alongside this graph to emphasise the differences observed. Repeat measures testing indicate one standard deviation is at a maximum of 6.7% of measured stresses.

The results show a significant difference in stress-strain response between the Silastic and PDMS silicone specimens. The PDMS specimen provides a far closer match to reference muscle tissue data particularly at low strains. There are however differences in the stress-strain response at higher strains, the strain hardening effect present in the PDMS specimen at approximately 0.6 strain, results in a significant deviation from the organic tissue properties. This may be attributed to the difference in respective polymer chain and collagen fibre lengths, which

cause a hardening effect at full elongation. Nevertheless, the graphs clearly illustrate a significantly improved simulation of relaxed muscle tissue under controlled uniaxial conditions.

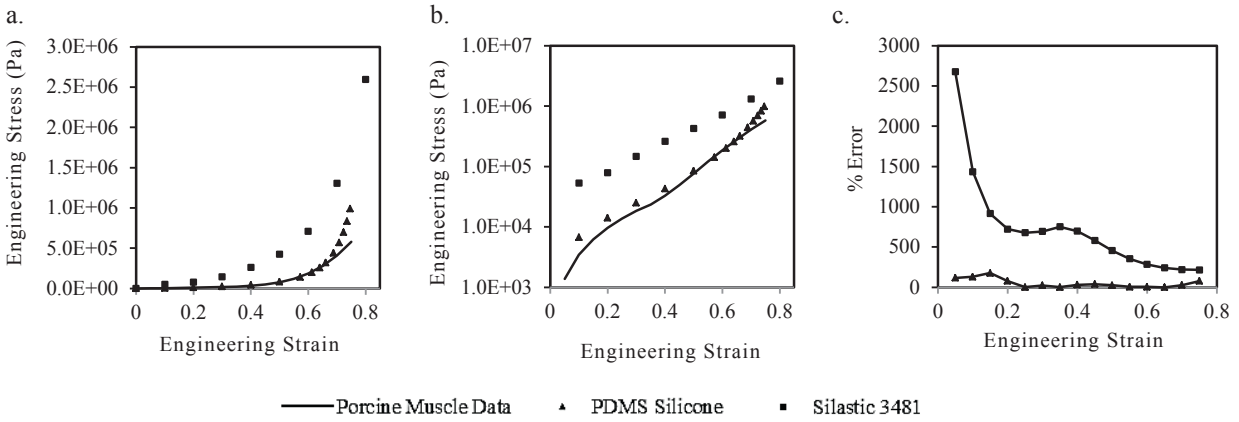

Figure 2 – (a) Linear stress-strain plot comparing compressive response of PDMS silicone and Silastic 3481 with porcine muscle tissue data; (b) Logarithmic stress-strain plot; (c) Percentage errors of silicones compared to porcine muscle data.

3.2. Constitutive Modelling

A two-term Ogden model was used to describe the constitutive behaviour of the proposed silicone under compressive loading conditions. The Ogden coefficients used are detailed in Table 1and are broadly comparable with those reported in similar work with soft hyperelastic materials (e.g. Briody et al., 2012).

$$W = \sum_{i=1}^{N} \frac{2\mu_i}{\alpha_i^2}\left(\bar{\lambda}_1^{\alpha_i} + \bar{\lambda}_2^{\alpha_i} + \bar{\lambda}_3^{\alpha_i} - 3\right) + \sum_{i=1}^{N} \frac{1}{D_i}(J_{el} - 1)^{2i} \quad (1)$$

Table 1- Ogden (N=2) model coefficients to describe the compressive response of the PDMS silicone

i	μ_i	α_i	D_i
1	$1.54\text{x}10^{4}$	2.31	$4.63\text{x}10^{-6}$
2	$2.05\text{x}10^{3}$	-3.75	0

3.3. Sports Impact Simulation

Figure 3 shows the maximum deformation of the synthetic and organic muscle tissue pucks, together with von Mises stress distribution predicted by the FEA.

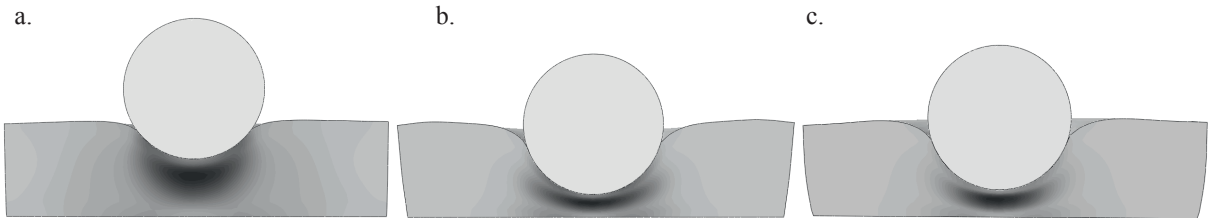

Figure 3 - FEA Images of pucks at maximum displacement: (a) Silastic 3481; (b). PDMS Silicone; (c) Muscle

The displacement-time histories exhibited by each puck are shown in Figure 4a. Displacement was selected as a parameter for comparison as the compression of muscular tissue against bone is widely suggested to be the key indicator for contusions (Crisco et al., 1996; McBrier et al., 2007; Desmoulin & Anderson, 2011). The stiffer Silastic elastomer experienced significantly lower displacements (48.2% difference at max. displacement) compared to muscle, whilst the PDMS silicone exhibited comparable results (5.4% difference at max. displacement).

Figure 4b. shows the von Mises stress relative to displacement. The graph shows that the PDMS silicone and organic muscle tissue surrogates exhibited a similar stress response up to approximately 85% displacement, where the silicone exhibits a greater stress response. It should be noted that all simulations were performed using isotropic material models, that represent the isotropic synthetic material behaviour, but fail to reproduce real muscle anisotropic response (e.g. due to collagen fibre orientation).

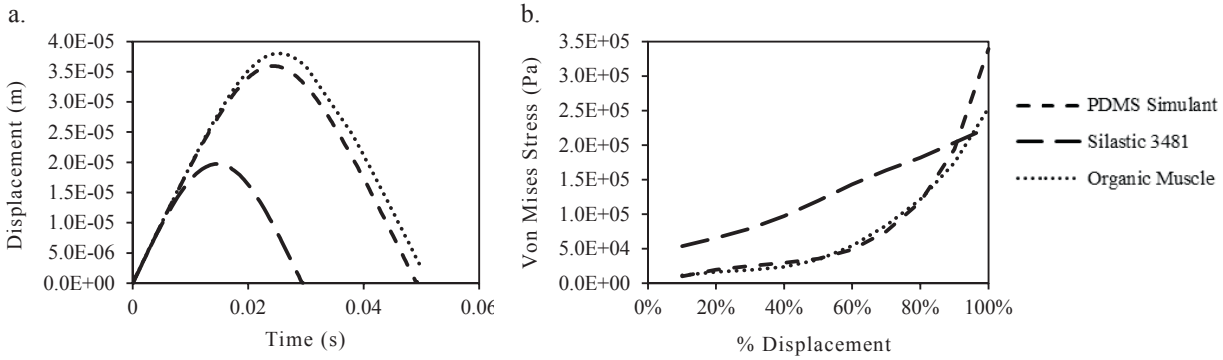

Figure 4 – (a) Displacement-Time graph for different surrogate materials; (b) von Mises stress criterion at different percentage displacements

4. Discussion

This study represents a first stage development of a more complex multi-tissue human surrogate for impact testing. Relaxed muscle is the initial primary focus as in many instances it constitutes the bulk of the soft tissue involved. The PDMS silicone provides a more accurate relaxed muscle simulant than Silastic 3481 and as such is relevant in surrogates for sports injury impact studies where affected muscle is not contracted (either in anticipation or due to the sports activity).

The PDMS silicone provides better simulation of the real muscle deformation behaviour than Silastic 3481; higher muscle compression is indicated that would correlate to a more severe contusion injury. The PDMS silicone did, however, show a significantly increased stress response at maximum displacement when compared to the organic tissue. Although the biofidelity of response is improved, the durability of a future surrogate, if the muscle region experiences these stresses, is reduced. More research is needed to determine whether this will be the case when the new material muscle is used in contact with a suitable skin material.

It is noted that Silastic 3481 was used in previous studies as a unified soft tissue simulant matching skin, subcutaneous and muscular soft tissue response. Phenomena causing injury (e.g. large compressive strain) or mitigating injury (e.g. stiff/soft tissue layer interaction to dissipate impact loads) are not well represented by its use. Areas for further research include skin and subcutaneous adipose tissue silicones which can provide a more accurate human response in their individual layers and when used together.

The variable stiffness introduced by different levels of muscular tonicity is also pertinent for consideration. More than one muscle simulant is needed to model both relaxed and contracted muscle behaviour to cover the full range of sports injury scenarios. Many studies have investigated the effect of contraction (Blackburn et al., 2009; Bensamoun et al., 2006; Wang, 2011; Zheng et al., 1999); however, current literature provides no conclusive opinion on the effects of different levels of contraction on the response of the tissue. Further research is required to develop a better understanding of the effects and aid the development of contracted muscle tissue simulants.

Although the PDMS simulant provides a much improved representation of the tissue response, further refinement of the polymer and cross linker concentrations could potentially develop a more biofidelic tissue. The lack of material data recorded at higher strain rates, more representative of those experienced in the sports impact simulation is a weakness of the study. A maximal strain rate of $14.8s^{-1}$ was recorded from the simulation, this value is low and the material behaviour is unlikely to deviate significantly from quasi-static properties however higher strain rate projectile impacts would require materials characterisation at representative strain rates. Similarly the viscoelastic properties need to be characterised to better understand the time dependent properties of the material; this is important to study in more dynamic impact scenarios.

5. Conclusions

Current soft tissue simulants only provide a gross representation of the global response of all tissues. To develop a more complete and biofidelic human surrogate, the mechanical behaviour of constituent tissues must be considered. The study presents the potential of an improved relaxed muscle simulant using additive cure silicones to simulate more biofidelic behaviour leading to more accurate consideration of injury. The developed silicone exhibited a much improved representation of this tissue under actual quasi-static and simulated intermediate strain rate compressive loading conditions.

References

Bensamoun, S.F., Ringleb, S.I., Littrell, L., Chen, Q., Brennan, M., Ehman, R.L. & An, K. 2006, "Determination of thigh muscle stiffness using magnetic resonance elastography", *Journal of Magnetic Resonance Imaging,* vol. 23, no. 2, pp. 242-247.

Blackburn, J.T., Bell, D.R., Norcross, M.F., Hudson, J.D. & Kimsey, M.H. 2009, "Sex comparison of hamstring structural and material properties", *Clinical Biomechanics,* vol. 24, no. 1, pp. 65-70.

Briody, C., Duignan, B., Jerrams, S. & Tiernan, J. 2012, "The implementation of a visco-hyperelastic numerical material model for simulating the behaviour of polymer foam materials", *Computational Materials Science,* vol. 64, pp. 47-51.

Comley, K. & Fleck, N. 2009, "The mechanical response of porcine adipose tissue", *ASME Journal of Biomechanical Engineering,* pp. 1-30.

Crisco, J., Hentel, K., Jackson, W., Goehner, K. & Jokl, P. 1996, "Maximal contraction lessens impact response in a muscle contusion model", *Journal of Biomechanics,* vol. 29, no. 10, pp. 1291-1296.

Desmoulin, G.T. & Anderson, G.S. 2011, "Method to Investigate Contusion Mechanics in Living Humans", *Journal of Forensic Biomechanics,* vol. 2, no. 1, pp. 1-10.

Halkon, B.J., Mitchell, S.R., Payne, T. & Carbo, J. 2014, "A biomechanics of human impacts in basketball", *The 2014 conference of the International Sports Engineering Association,* PAPER_ID_257 [EXPECTED PRINT].

Hrysomallis, C. 2009, "Surrogate thigh model for assessing impact force attenuation of protective pads", *Journal of Science and Medicine in Sport,* vol. 12, no. 1, pp. 35-41.

McBrier, N.M., Neuberger, T., Okita, N., Webb, A. & Sharkey, N. 2009, "Reliability and validity of a novel muscle contusion device", *Journal of athletic training,* vol. 44, no. 3, pp. 275.

McElhaney, J.H. 1966, "Dynamic response of bone and muscle tissue", *Journal of applied physiology,* vol. 21, no. 4, pp. 1231-1236.

Ní Annaidh, A., Bruyère, K., Destrade, M., Gilchrist, M.D. & Otténio, M. 2012, "Characterization of the anisotropic mechanical properties of excised human skin", *Journal of the Mechanical Behavior of Biomedical Materials,* vol. 5, no. 1, pp. 139-148.

Payne, T., Mitchell, S. & Bibb, R. 2013, "Design of human surrogates for the study of biomechanical injury: a review", *Critical Reviews™ in Biomedical Engineering,* vol. 41, no. 1, pp. 51-89.

Petrone, N., Tamburlin, L., Panizzolo, F. & Atzori, B. 2010, "Development of an instrumented anthropomorphic dummy for the study of impacts and falls in skiing", *Procedia Engineering,* vol. 2, no. 2, pp. 2587-2592.

Roberts, J., Merkle, A., Biermann, P., Ward, E., Carkhuff, B., Cain, R. & O'Connor, J. 2007, "Computational and experimental models of the human torso for non-penetrating ballistic impact", *Journal of Biomechanics,* vol. 40, no. 1, pp. 125-136.

Shergold, O.A., Fleck, N.A. & Radford, D. 2006, "The uniaxial stress versus strain response of pig skin and silicone rubber at low and high strain rates", *International Journal of Impact Engineering,* vol. 32, no. 9, pp. 1384-1402.

Song, B., Chen, W., Ge, Y. & Weerasooriya, T. 2007, "Dynamic and quasi-static compressive response of porcine muscle", *Journal of Biomechanics,* vol. 40, no. 13, pp. 2999-3005.

Wang, C., Zheng, Y., Xiao, Y., Qiu, W. & Zheng, H. 2012, "Using vibro-ultrasound method to assess the vastus intermedius stiffness over the entire range of step isometric contraction of knee extensors", *Ultrasonics Symposium (IUS), 2012 IEEE International*, Dresden, Germany, 7th-10th October 2012, pp. 1351.

Zheng, Y., Mak, A.F. & Lue, B. 1999, "Objective assessment of limb tissue elasticity: development of a manual indentation procedure", *Journal of rehabilitation research and development,* vol. 36, no. 2, pp. 71-85.