1. Introduction

Consumer, consciously or not, tend to touch and feel the surface of the goods and then make a judgment about whether they like this feel or not. This subjective judgment has been recognized as a key factor to win or lose customers for industries where personal taste on touch-feel perception will be a main purchase criterion. A thorough understanding of the mechanical interaction between product and skin, like the friction and deformation behavior of skin, is essential in the development of human-product interfaces, and this is important in establishing safety margins.

Tests on animals, humans, cadavers, and explants have been traditionally used to study materials-skin interactions. But unfortunately, measurement of the mechanical and frictional behavior of human skin in vivo has several disadvantages: experiments on human and animal skin raise ethical issues, and these samples are hard to obtain, expensive and give rise to highly variable results. The measurements often suffer from poor reproducibility due to person-to-person variability and involuntary human motions during testing. And the possibility of skin damage limits the severity of the conditions that can be applied. For the reasons above, many mechanical and tribological studies on products involving human skin contact attempt to use physical skin models. Physical skin models have the advantage of obtaining long-term stability, lower costs, easy storage and manipulation, and their physical properties are easier to control, thus are desirable in providing objective and reproducible results within a reasonable time-frame. Moreover, physical skin models can be used for the design and experimental testing of functional surface features on medical, healthcare and consumer products that have a physical interaction with the skin, such as certain healthcare devices and tools, cosmetic skin care products and devices, shavers, buttons and touch-screens, etc.

Physical human skin models, which were usually developed for the needs of testing, calibration, quality check of devices, or teaching have been proposed and described in numerous studies concerning testing and development of materials and methods. This review article gives an overview of the development of physical skin model for biomechanical applications, in which the progresses made in the synthesis and the following tests of skin-materials interaction were summarised and discussed.
2. The structure and mechanical property of human skin

A thorough investigation of the structure and mechanical property of human skin should be made before we attain a breakthrough in the development of physical skin model with appropriate skin properties.

Structurally, skin is a complex multi-layered tissue and has three main layers which are the epidermis, dermis and hypodermis layer. The epidermis is the outermost layer of skin. It is as thin as approximately 0.5 mm to 1.5 mm. It is built up of five distinct layers which are stratum corneum, stratum lucidum, stratum granulosum, stratum spinosum and stratum basale respectively. The second main layer of human skin controls skin strength and flexibility, and it is called dermis which is reinforced by collagen and elastin fibres and has a thickness of approximate around 0.8 mm to 2 mm. The bottom layer of skin is hypodermis, which is an extremely viscous and soft hypodermis layer known as “subcutis” or “subcutaneous fat”. It acts as the supportive structure that connects underlying muscle to the skin, and has an approximate thickness of around 0.8 mm.

Functionally, skin acts as a protector for the inner tissue from mechanical and ultraviolet damage, and it helps avoiding excessive water loss. In addition, it acts as an insulator and body temperature controller as well.

Biomechanically, researchers around the world are working aggressively on the investigation of biomechanical properties of skin. Because the knowledge of biomechanical properties of skin is essential to some clinical applications, such as measuring skin elasticity and surgical planning, understanding the mechanism on skin ageing and sensory signaling, virtual needle insertion simulation, and minimally invasive surgical training, etc. As reported, skin is highly non-linear, anisotropic, heterogeneous, viscoelastic material. A wide range of values for the elastic modulus of the various skin layers is reported in the literature, which shows that the elastic modulus of dry and wet stratum corneum, viable epidermis, and dermis are 3.5-1000 MPa, 10-50 MPa, 1.5 MPa, 8-35 kPa, respectively. And these values are affected by skin hydration status, environment humidity, test method, test condition, etc.

3. Classification of physical skin model for biomechanical applications

Many physical skin models have been developed with synthetic polymers to mimic the mechanical and tribological performance of the human skin in various conditions and against various materials for different applications, which are produced based on numerous combinations of materials, structures, and morphologies, including but not limited to liquid suspensions, gelatinous substances, resins, metals, elastomers, and textiles incorporating nano- and micro-fillers.

According to their main types and characteristics, the most commonly used physical skin model for biomechanical applications can be easily classified as gelatinous substances, elastomers, and combinations.

3.1 Gelatinous substances

Skin models based on substances have an ability to interact with water, and lead to reversible creation of gels. This property makes it possible to modify and control various physical, mechanical and chemical properties, such as elastic modulus, hardness, optical, or surface properties. Moreover, specific behaviour of gelatin and related polymers can be influenced by pressure, pH and temperature, which can lead to further variability in properties. Gelatinous substances used in the skin models including gelatine, collagens, agar, agarose, and polyvinyl alcohol gels, etc.

3.1.1 Gelatine

Gelatine is an irreversibly hydrolyzed form of collagen. It has broad molecular weight ranges associated with physical and chemical methods of denaturation. It is an abundant component of the skin, bones, and the connective tissue, and is commonly used as a gelling agent in food, photography, pharmaceutical drugs, vitamin capsules, and cosmetic manufacturing. Dry gelatin has a long shelf live. J. Jussila has described the use of gelatine as skin model for ballistic testing as well as wound ballistic forensic reconstructions. In order to get a skin substitute for adhesion-to-skin evaluation, I. Lir, et al. reported a synthetic skin, the composition of which is based on gelatin plasticized by glycerol, polysaccharides, and a mixture of lipids that mimicked the skin’s lipid structure and created a hydrophobic surface. The results obtained show that the mechanical and surface properties of the model material are close to those of the human skin.

3.1.2 Polyvinyl alcohol gels

Poly (vinyl) alcohol (PVA) is an atactic material that exhibits crystallinity. It is highly soluble in water, and after cross-linking can form hydrogels. PVA has many advantages such as excellent film forming, emulsifying, adhesive, high oxygen and aroma barrier properties, high tensile strength and flexibility. And it is resistant to oil, grease and solvents. These properties are dependent on humidity. For example, the water will acts as a plasticizer, and reduce its tensile strength, but
increase its elongation and tear strength. Therefore, PVA is a well-known polymer widely used in medical applications due to its biocompatibility and easy manufacturing characteristics. Besides, many researches are also chosen it as building blocks for making physical skin model for biomechanical applications.

It has been reported that PVA is regarded as a skin and soft tissue phantom for magnetic resonance techniques39, optical tomography30, and X-ray examination31. The mechanical properties of PVA cryogels are tunable within the range of those of soft tissues30. Kim et al. proposed the usage of PVA thin films as a skin model to collect data for designing a computer game controller39.

To develop physical skin model for the studying the mechanical and tribological behavior of artificial turf and shaver, M. Morales Hurtado et al.39 synthesized pure PVA and PVA mixed with Cellulose (PVA-Gel) via freezing-thawing cycles to represent epidermis and dermis respectively. The two layers are combined together as a 2-layered skin model (2LSM) by using a specially designed mould. Moreover, the PVA top layer is moulded with surface texture to mimic the surface structure and surface roughness of human skin. Dynamic mechanical analysis and creep tests were used to study the mechanical properties of the developed skin model, and it is found that the elastic moduli are 38 kPa and 50 kPa for PVA and PVA-Gel, respectively. Micro-indentation tests were conducted as well and results indicate that the elastic modulus is in the same range of the dynamic tests, which are 45-55 kPa for PVA and 56-81 kPa for PVA-Gel. More important, the developed 2LSM exhibits a gradient of hydration comparable to the human skin, as evaluated by using Corneometer.

3.2 Elastomers

Elastomers are polymers exhibiting rubber-like viscoelastic properties, which are similar to those of human skin44,46, and the physical properties based on elastomer can be changed within a wide range. The elastomers include but not limited to silicones, polyurethane, etc.

3.2.1 Silicone

Silicones, also known as polysiloxanes, are polymers that include any inert, synthetic compound made up of repeating units of siloxane, which is a chain of alternating silicon atoms and oxygen atoms, frequently combined with carbon and/or hydrogen47.

Silicone is a commonly and widely used material to construct physical skin model. The main advantages of silicone based models are related to the broad range of properties that can be simulated, easy manipulation, nontoxicity during and after preparation, and long-term stability. And it is easy to produce surface morphologies with defined roughness as well as obtaining replicas directly from skin, enabling the investigation on the role of roughness in measurements38. Moreover, skin models containing silicone are durable over long time periods and can be moulded to obtain various shapes.

Silicone based skin models have been introduced to simulate skin in numerous applications such as optical imaging, measurement of the specific absorption rate42, drug delivery42,43, needle penetration42,43, acoustic and photoacoustic imaging44, tactile assessment45, and friction43,47. For instance, a commercially available product, Dragon Skin46, is a kind of silicone rubber, which is used for a variety of applications, ranging from the creation of skin effects to medical prosthetics and cushioning applications. It was prepared by the mixture of equal amounts of two components followed by degassing. Then, the mixtures were poured into a casting mold and cured at 65 °C for 24 h to form the final products.

As for biomechanical applications, O. A. Shergold et al.43 has compared the mechanical properties of three commonly used silicone polymers, which are silicone rubber, natural rubber, and natural butyl rubber, with those of human skin. They found that compared with the other two polymers, silicone rubbers are an approximate substitute for human skin, because the tear strength and tensile strength of silicone rubber are comparable to those for human skin, and they have a somewhat higher modulus, a lower rate of strain hardening and a comparable toughness.

Recent studies have also shown that the friction and traction properties of polysiloxane systems exhibit many features of human skin49. Silicone skin L7350, a silicone rubber, was used as skin model by the Federation Internationale de Football Association (FIFA) to investigate the adequacy and quality of the turf by evaluating the abrasion and friction during sliding contact with artificial grass. And E. van der Heide, et al.50 used it as one of the contacting surface representing skin to evaluate the tribological performance of surface coating for the development of low friction skin contacting product. G. Zhang et al.51 also used Silicone Skin L7350 as a skin model to study the effect of surgical suture structure and operational condition on the surgical suture friction.

In order to evaluate the frictional feel of textiles, Ramkumar et al.52,53 have developed a polymeric finger produced by the silicone replication technique and used as skin equivalent. The polymeric finger sledge successfully characterized the frictional properties of a set of 1 × 1 rib-knitted cotton fabrics.

Silicone is hydrophobic and cannot interact with water, which is quite different to human skin. In order to develop moisture-sensitive skin model, M. Nachman, et al.53 proposed
a new composite 2-layer artificial skin model, in which a new class of hydrophilic silicone rubber which is relatively stiff and moisture-absorbing is used as the material for the top layer-epidermis, and a further three synthetic materials, silicone rubber from Wacker™, the Technogel® and the polyurethane gel from NorthstarPolymers™, are tested as potential soft under-layer materials, representing the dermis and hypodermis. Details on the hydrophilic silicone rubber can be found in patent US 20140113986 A1. These silicones are based on standard silicones but modified with strongly hydrophilic alpha-olefin sulfonate. Under both dry and moist skin conditions, the friction and deformation behaviour of the 2-layer artificial skin model is comparable to those of human skin. This development has potential for use as a test-bed in the development of devices that interact with the skin in a mechanical way.

### 3.2.2 Polyurethane

Polyurethane is copolymers from urethanes groups produced by a conjugation between diol and di-isocyanate groups via polymerization reaction. It has a long shelf life and stability and with tunable properties. Due to their viscoelastic properties, polyurethanes are another kind of widely used materials for making mechanical skin models. Polyurethane skin models can be found for training in the medical area, e.g. in intradermal injection, skin surgery or prediction of softness of real human skin, where polyurethane simulates the epidermis. Polyurethane sponges have been shown to simulate the human dermis in the biomechanical modelling of non-ballistic skin wounding.

The representative polyurethane skin model is Lorica artificial leather, consisting of polyamide microfleece coated with polyurethane. It was developed for realistically simulating human skin friction against textiles under dry conditions. In addition to friction properties, the Lorica skin model reproduces surface properties of human skin and shows similar force-deformation characteristics. Derler et al. investigated the friction properties of polyvinyl siloxane, steel, brass, silicone material and Lorica. And it is found that Lorica shows the best correspondence with human skin under dry conditions. Therefore, Lorica has been applied to study the friction of functional medical textile and hospital bed sheets.

Tiezzi et al. reported a robotic finger made of a polyurethane gel, which shows a softness quite close to that of the human skin, a nonlinear viscoelastic behaviour and other promising features.

To study the interaction between skin and hair, Bharat Bhushan et al. have used a polyurethane film to represent human skin. It has a thickness of approximately 3 mm, and with a similar surface energy to human skin. Friction and wear experiments to simulate skin-hair contacts at nominal conditions were successfully performed using a flat-on-flat tribometer on three different kinds of hair against polyurethane film.

### 3.3 The combinations

As described in section 2, human skin has a layered structure, and each layer has different components, thickness and mechanical properties. Therefore, sometimes it is difficulty to make an expected physical skin model by using only one kind of materials. Researchers have also developed varies kinds of physical skin models by the combination of different kinds of materials in order to either better simulating the layered structure with changing mechanical properties, or better mimicking the hydration effect of human skin. Details of these combinations are illustrated as below.

### 3.3.1 Silicone and polyurethane

To study the blistering mechanism of human skin, C. Guerra et al. developed a Synthetic Skin Simulant Platform (3SP), a tri-layer design which can reproduce the mechanical behavior of human skin when exposed to tribological loading. The 3SP is an assembled construct of bonded elastomeric layers that act as surrogates for the epidermis, basement membrane, dermis, and subdermal structure. The top layer consists of 0.8 mm thick transparent silicone rubber, referring to as the epidermal simulant layer (ESL) to simulate the stratum corneum. The dermal simulant layer (DSL) consisted of a 3.18 mm thick layer of either polyurethane elastomer (McMaster-Carr, 4000 durometer) or neoprene rubber. A flat plate was pressed against the top of the ESL immediately after establishing contact with the DSL to produce smooth bonding across the interface. To avoid the substrate effects when only using ESL and DSL, a subdermal simulant layer (SSL) was incorporated, which is a 3.18 mm thick latex rubber. A silicone-based adhesive was used to join the DSL to the SSL. The 3SP allows for modulation of friction coefficient, interfacial adhesion strength, and subdermal stiffness for investigation of blistering damage to various anatomical sites. Experimental results have been compared to human test data and have shown that the 3SP provides the potential to make significant advances with respect to skin tribology research.

### 3.3.2 PVA and silicone

As discussed in section 3.2.1, in order to simulate the moisture-absorbing properties of human skin, M. Nachman has developed a skin model by using hydrophilic alpha-olefin sulfonate modified silicone rubber. With the same target
in mind, M. Morales-Hurtado et al.\(^7\) has developed a new epidermal skin equivalent (ESE), based on an interpenetrating network made by the combination of hydrophobic polydimethylsiloxane (PDMS) and hydrophilic PVA hydrogel cross-linked with glutaraldehyde, to mimic the mechanical properties of the human skin structure, variable with the length scale. The developed ESE showed similar surface and bulk properties to those of targeting human skin, with surface roughness Ra about 14-16 µm and contact angle between 50-80 deg, with hydration level varied with humidity. The mechanical performance was determined by indentation tests and Dynamic Thermo Mechanical Analysis (DTMA) shear measurements. The indentation results show an elastic modulus between 0.1-1.5 MPa, depending on the water content, which is in good agreement with that of the target epidermis reported in the literature. According to the DTMA measurements, the ESE exhibits a viscoelastic behavior, with a shear modulus between 1-2.5 MPa variable with temperature, frequency and hydration of the samples. Moreover, the tribological tests of ESE against different contact materials show similar friction coefficient to that of isolated human skin, and increased friction under high temperature and humidity\(^7\).

3.3 Polyvinylidene fluoride, silicone gel

Polyvinylidene fluoride, or polyvinylidene difluoride (PVDF), is a highly non-reactive thermoplastic fluoropolymer produced by the polymerization of vinylidene difluoride. It is a specialty plastic used in applications requiring the highest purity, as well as resistance to solvents, acids and bases. PVDF has a glass transition temperature \(T_g\) of about-35°C, and compared to other fluoropolymers, PVDF has a low density (1.78 g/cm\(^3\)).

Fei Shao et al.\(^9\) developed a haptic finger made of a polyvinylidene fluoride piezopolymer film. The film consists two layers, which represent skin and soft tissue respectively. The outer layer is an encapsulated silicone with a thin acrylic layer to represent skin. And the inner one is a combination of silicone elastomer and gel base to represent soft tissue. To study the component effect on the frictional behavior of the artificial fingertip, two types of multi-layer artificial fingertip were made. One, named the elastic artificial fingertip, has as its inner layer a gel base with an equal proportion (100%) of elastomer. The other, named the hysteresis artificial fingertip, has as its inner layer a gel base with 60% proportion of elastomer. By evaluating the friction behavior of the artificial fingertips, it is found that the artificial fingertip becomes more hysteretic when the proportion of silicone gel becomes higher, and the hysteresis artificial fingertip has both the same compliance and same hysteresis as a real finger. While both the hysteresis and elastic artificial fingertips mimic real behavior of real finger better than the silicone tip, when considering the sliding friction coefficients.

4. Conclusion

Facing the fact that measurements of the mechanical and frictional behavior of human skin in vivo has many disadvantages, the development of physical skin as human skin equivalent is essential. In the past decades, many physical human skin models have been proposed with synthetic polymers to mimic the mechanical and tribological performance of the human skin in various conditions and against various materials for different applications, which are produced based on numerous combinations of materials, structures, and morphologies. However, most of them can mimic human skin only in one or a few aspects or conditions, while show different properties from real skin in the others. In addition, taking into account that human skin has a complex structure, the effective combination of a variety of materials may be the trend of artificial skin development. Further research is required to investigate the mechanical properties of human skin and develop appropriate techniques in estimating the skin properties which are valuable to the development of biomechanics study of human skin.

Acknowledgement

The authors are grateful to the Shanghai Natural Science Foundation (Grant no. 17ZR1442100) and the Shanghai Municipal “Science and Technology Innovation Action Plan” International Cooperation Project (Grant no. 15540723600) for the financial support.

References

1) Liu, X., Chan, M. K., Hennessey, B., Rübenach, T. and Alay, G.: Quantifying touch-feel perception on automotive interiors by multi-function tribological probe microscop, Journal of Physics: Conference Series, 13, 357-361, (2005).
2) Van Der Heide, E., Lossie, C. M., Van Bommel, K. J. C., Reinders, S. A. F. and Lenting, H. B. M.: Experimental Investigation of a Polymer Coating in Sliding Contact with Skin-Equivalent Silicone Rubber in an Aqueous Environment, Tribology Transactions, 53(6), 842-847, (2010).
3) Wang, Y., Marshall, K. L., Baba, Y., Gerling, G. J. and Lumpkin, E. A.: Hyperelastic Material Properties of Mouse Skin under Compression, PLoS ONE, 8(6), e67439, (2013).
4) Mahmud, L., Manan, N. F. A., Ismail, M. H. and Mahmud,
9) J.: Characterisation of soft tissues biomechanical properties using 3D Numerical Approach, 2013 IEEE Business Engineering and Industrial Applications Colloquium (BEIAIC), 801-806, (2013).

5) Su, J., Zou, H. and Guo, T.: The Study of Mechanical Properties on Soft Tissue of Human Forearm in Vivo, 2009 3rd International Conference on Bioinformatics and Biomedical Engineering (ICBBE), 1-4, (2009).

6) Wan Abas, W. A. B. and Barbenel, J. C.: Uniaxial tension test of human skin in vivo, Journal of Biomedical Engineering, 4(1), 65-71, (1982).

7) Derler, S. and Gerhardt, L.-C.: Tribology of Skin: Review and Analysis of Experimental Results for the Friction Coefficient of Human Skin, Tribology Letters, 45(1), 1-27, (2012).

8) Franklin, S. E., Baranowska, J., Furgala, J. and Piwowarczyk, J.: Friction of natural human, porcine and synthetic skin, Proc. 5th International Conference on Mechanics of Biomaterials and Tissues, 8-12, (2013).

9) Kwiatkowska, M., Franklin, S. E., Hendriks, C. P. and Kwiatkowski, K.: Friction and deformation behaviour of human skin, Wear, 267(5-8), 1264-1273, (2009).

10) Geerligs, M., van Breezen, L., Peters, G., Ackermans, P., Baaijens, F and Oomens, C.: In vitro indentation to determine the mechanical properties of epidermis, Journal of Biomechanics, 44(6), 1176-1181, (2011).

11) Pailler-Mattei, C., Bec, S. and Zahouani, H.: In vivo measurements of the elastic mechanical properties of human skin by indentation tests, Medical Engineering & Physics, 30(5), 599-606, (2008).

12) van Kuilenburg, J., Masen, M. A., and van der Heide, E.: Contact modelling of human skin: What value to use for the modulus of elasticity?, J Engineering Tribology, 227(4), 349-361, (2012).

13) Guerra, C. and Schwartz, C. J.: Development of a Synthetic Skin Simulant Platform for the Investigation of Dermal Blistering Mechanics, Tribology Letters, 44, 223-228, (2011).

14) Guerra, C. and Schwartz, C. J.: Investigation of the influence of textiles and surface treatments on blistering using a novel simulant, Skin Research and Technology, 18(1), 94-100, (2012).

15) Cottenden, D. J. and Cottenden, A. M.: A study of friction mechanisms between a surrogate skin (Lorica soft) and nonwoven fabrics, Journal of the Mechanical Behavior of Biomedical Materials, 28, 410-426, (2013).

16) Gerhardt, L. C., Mattle, N., Schrade, G. U., Spencer, N. D. and Derler, S.: Study of skin-fabric interactions of relevance to decubitus: friction and contact-pressure measurements, Skin Research and Technology, 14(1), 77-88, (2008).

17) Muhammad, H. B.: Development of a bio-inspired MEMS based tactile sensor array for an artificial finger, Doctoral Thesis, University of Birmingham, (2011).

18) Koc, I. M. and Aksu, C.: Tactile sensing of constructional differences in fabrics with a polymeric finger tip, Tribology International, 59, 339-349, (2013).

19) Shao, F., Childs, T. H. C. and Henson, B.: Developing an artificial fingertip with human friction properties, Tribology International, 42(11-12), 1575-1581, (2009).

20) Bhushan, B. and Tang, W.: Surface, tribological, and mechanical characterization of synthetic skins for tribological applications in cosmetic science, Journal of Applied Polymer Science, 120(5), 2881-2890, (2011).

21) Skedung, L., Buraczewska-Norin, I., Dawood, N., Rutland, M. W. and Ringstad, L.: Tactile friction of topical formulations, Skin Research & Technology, 22(1), 46-54, (2016).

22) Chimata, G. and Schwartz, C. J.: Investigation of the effect of the normal load on the incidence of friction blisters in a skin-simulant model, Proceedings of the Institution of Mechanical Engineers, Part J, Journal of Engineering Tribology, 229(3), 266-272, (2015).

23) Kozlov, P. V. and Burdygina, G. I.: The structure and properties of solid gelatin and the principles of their modification, Polymer, 24(6), 651-666, (1983).

24) Glicksman, M.: Gum technology in the food industry, New York: Academic Press, (1969).

25) Dąbrowska, A. K., Rotaru, G. M., Derler, S., Spano, F., Camenzind, M., Annaheim, S., Stämpfli, R., Schmid, M. and Rossi, R. M.: Materials used to simulate physical properties of human skin, Skin Research & Technology, 22(1), 3-14 (2016).

26) Jussila, J.: Preparing ballistic gelatin-review and proposal for a standard method, Forensic Science International, 141(2-3), 91-98, (2004).

27) Lir, I., Haber, M. and Dodik-Kenig, H.: Skin surface model material as a substrate for adhesion-to-skin testing, Journal of Adhesion Science and Technology, 21(15), 1497-1512, (2007).

28) Baker, M. I., Walsh, S. P., Schwartz, Z. and Boyan, B. D.: A review of polyvinyl alcohol and its uses in cartilage and orthopedic applications, Journal of Biomedical Materials Research, 100(5), 1451-1457, (2012).

29) Iravani, A., Mueller, J. and Yousefi, A. M.: Producing homogeneous cryogel phantoms for medical imaging: a finite-element approach, Journal of Biomaterials Science, Polymer Edition, 25(2), 181-202, (2014).

30) Lamouche, G., Kennedy, B. F., Kennedy, K. M., Bisaillon, C. E., Curatolo, A., Campbell, G., Pazos, V. and Sampson, D.
31) Price, B. D., Gibson, A. P., Tan, L. T., and Royle, G. J.: An elastically compressible phantom material with mechanical and x-ray attenuation properties equivalent to breast tissue, Physics in Medicine and Biology, 55(4), 1177-1188, (2010).

32) Kim, D. H., Lu, N., Ma, R. Kim, Y. S., Kim, R. H., Wang, S., Wu, J., Won, S. M., Tao, H., Islam, A., Yu, J. K., Kim, T., Chowdhury, R., Ying, M., Xu, L., Li, M., Chung, H. J., Keum, H., McCormick, M., Liu, P., Zhang, Y. W., Omenetto, F. G., Huang, Y., Coleman, T. and Rogers, J. A.: Epidermal Electronics, Science, 333(6044), 838-843, (2011).

33) Hurtado, M. M., de Vries, E. G., Zeng, X. and van der Heide, E.: A tribo-mechanical analysis of PVA-based building-blocks for implementation in a 2-layered skin model, Journal of the Mechanical Behavior of Biomedical Materials, 62, 319-332, (2016).

34) Aleman, J., Chadwick, A. V., He, J., Hess, M., Horie, K., Jones, R. G., Kratochvil, P., Meisel, I., Mita, I., Moad, G., Penczek, S. and Stepto, R. F. T.: Definitions of terms relating to the structure and processing of gels, gels, networks, and inorganic-organic hybrid materials (IUPAC Recommendations 2007), Pure and Applied Chemistry, 79(10),1801-1829, (2007).

35) Abdou-Sabet, S., Puydk, R. C. and Rader, C. P.: Dynamically vulcanized thermoplastic elastomers, Rubber Chemistry Technology, 69(3), 476-494, (1996).

36) Jacchowicz, J., McMullen, R. and Prettypaul, D.: Indentometric analysis of in vivo skin and comparison with artificial skin models, Skin Research & Technology, 13(3), 299-309, (2007).

37) Moretto, H. H., Schulze, M. and Wagner, G.: Silicons, Ullmann's Encyclopedia of Industrial Chemistry, Wiley-VCH, (2000).

38) Derler, S., Schrade, U. and Gerhardt, L. C.: Tribology of human skin and mechanical skin equivalents in contact with textiles, Wear, 263(7-12), 1112-1116, (2007).

39) Gabriel, C.: Tissue equivalent material for hand phantoms, Physics in Medicine and Biology, 52(14), 4205-4210, (2007).

40) Leveque, N., Raghavan, S. L., Lane, M. E. and Hadgraft, J.: Use of a molecular form technique for the penetration of supersaturated solutions of salicylic acid across silicone membranes and human skin in vitro, International Journal of Pharmaceutics, 318(1-2), 49-54, (2006).

41) Khan, G. M., Frum, Y., Sarheed, O., Eccleston, G. M. and Meidan, M. V.: Assessment of drug permeability distributions in two different model skins, International Journal of Pharmaceutics, 303(1-2), 81-87, (2005).

42) Aoyagi, S., Izumi, H. and Fukuda, M.: Biodegradable polymer needle with various tip angles and consideration on insertion mechanism of mosquito’s proboscis, Sensors and Actuators A: Physical, 143, 20-28, (2008).

43) Shergold, O. A. and Fleck, N. A.: Experimental investigation into the deep penetration of soft solids by sharp and blunt punches, with application to the piercing of skin, Journal of Biomechanical Engineering, 127(5), 838-848, (2005).

44) Zell, K., Sperl, J. I., Vogel, M. W., Niessner, R. and Haisch, C.: Acoustical properties of selected tissue phantom materials for ultrasound imaging, Physics in Medicine and Biology, 52(20), N475-N484, (2007).

45) Tomimoto, M.: The frictional pattern of tactile sensations in anthropomorphic fingertip, Tribology International, 44(11), 1340-1347, (2011).

46) Morales-Hurtado, M., Zeng, X., Gonzalez-Rodriguez, P., Ten Elshof, J. E. and van der Heide, E.: A new water absorbable mechanical Epidermal skin equivalent: the combination of Hydrophobic PDMS and hydrophilic PVA hydrogel, Journal of the Mechanical Behavior of Biomedical Materials, 46, 305-317, (2015).

47) FIFA I. FIFA Quality Concept for Football Turf Handbook of Test Methods, (2012).

48) Soroushian, P. and Lu, J.: Technova corporation, Lansing, Michigan, Personal Communication, (2009).

49) Ramkumar, S. S., Wood, D. J., Fox, K. and Harlock, S. C.: Developing a Polymeric Human Finger Sensor to Study the Frictional Properties of Textiles Part I: Artificial Finger Development, Textile Research Journal, 73(6), 469-473, (2003).

50) Zeng, X. and van der Heide, E.: Bio-inspired tribological interfaces design for reducing friction in sliding contacts with skin equivalent in aqueous lubrication system, In Proceedings of Bio-inspired Materials, Potsdam, Germany, 26, (2012).

51) Zhang, G., Ren, T., Zeng, X. and Van Der Heide, E.: Influence of surgical suture properties on the tribological interactions with artificial skin by a capstan experiment approach, Friction, 5(1): 87-98, (2017).

52) Ramkumar, S. S., Wood, D. J., Fox, K. and Harlock, S. C.: Developing a Polymeric Human Finger Sensor to Study the Frictional Properties of Textiles Part II: Experimental Results, Textile Research Journal, 73(7), 606-610, (2003).

53) Nachman, M. and Franklin, S. E.: Artificial Skin Model simulating dry and moist in vivo human skin friction and deformation behaviour, Tribology International, 97, 431-439, (2016).
54) Cooper, S. L. and Tobolsky, A. V.: Properties of linear elastomeric polyurethanes, Journal of Applied Polymer Science, 10(12), 1837-1844, (1966).
55) Elleuch, K., Elleuch, R. and Zahouani, H.: Comparison of elastic and tactile behavior of human skin and elastomeric materials through tribological tests, Polymer Engineering & Science, 46(12), 1715-1720, (2006).
56) Bjellerup, M.: Novel method for training skin flap surgery: polyurethane foam dressing used as a skin equivalent, Dermatologic Surgery, 31, 1107-1111, (2005).
57) Nakatani, M., Fukuda, T., Sasamoto, H., Arakawa, N., Otaka, H., Kawaiue, T. and Omata, S.: Relationship between perceived softness of bilayered skin models and their mechanical properties measured with a dual-sensor probe. International Journal of Cosmetic Science, 35, 84-88, (2013).
58) Whittle, K., Kieser, J., Ichim, L., Swain, M., Waddell, N., Livingstone, V. and Taylor, M.: The biomechanical modelling of non-ballistic skin wounding: blunt-force injury, Forensic Science, Medicine, and Pathology, 4, 33-39, (2008).
59) Niedermann, R., Wyss, E., Annaheim, S., Psikuta, A., Davey, S. and Rossi, R. M.: Prediction of human core body temperature using non-invasive measurement methods, International Jounal of Biometeorol, 58, 7-15, (2014).
60) Colas, A. and Curtis, J.: Silicone biomaterials: history and chemistry, Biomaterials science: an introduction to materials in medicine, San Diego: Elsevier Academic Press, 80-85, (2004).
61) Derler, S., Rotaru, G. M., Ke, W., El Issawi-Frischknecht, L., Kellenberger, P., Scheel-Sailer, A. and Rossi, M. R.: Microscopic contact area and friction between medical textiles and skin, Journal of the Mechanical Behavior of Biomedical Materials, 38, 114-125, (2014).
62) Tiezzi, P., Lotti, F. and Vassura, G.: Polyurethane Gel Pulps for Robotic Fingers, In: 11th International Conference on Advanced Robotics, (2003).
63) Bhushan, B., Wei, G. and Haddad P.: Friction and wear studies of human hair and skin, Wear, 259(7-12), 1012-1021, (2005).
64) Morales-Hurtado, M., Peppelman, M., Zeng, X., van Erp, P. E. J. and Van Der Heide, E.: Tribological behavior of skin equivalents and ex-vivo human skin against the material components of artificial turf in sliding contact, Tribology International, 102, 103-113, (2016).