Human Roughness Perception and Possible Factors Effecting Roughness Sensation

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Abstract

Surface texture sensation is significant for business success, in particular for solid surfaces for most of the materials; including foods, furniture or fabrics. Applications of roughness perception are still unknown, especially under different conditions such as lubricants with varying viscosities, different temperatures, or under different force loads during the observation of the surface. This work aims to determine the effect of those unknown factors, with applied sensory tests on 62 healthy participants. Roughness sensation of fingertip was tested under different lubricants including water and diluted syrup solutions at room temperature (25°C) and body temperature (37°C) by using simple pair-wise comparison in order to observe the just noticeable difference threshold and perception levels. Additionally in this research applied force load during roughness observation was tested with pair-wise ranking method to illustrate its possible effect on the human sensation. Obtained results showed that human roughness discrimination capability reduces with an increasing viscosity of the lubricant, where the temperature was not found to be significant. Moreover, the increase in the applied force load showed an increase in the sensitivity of roughness discrimination capability. Observed effects of the applied factors were also used for estimating the oral sensation of texture during eating. These findings are significant for our fundamental understanding to the texture perception, but also could find applications in the material sciences which may include food sciences that needs information about texture perception for the development of new foods with controlled textural features.

Practical Applications

Texture discrimination ability, more specifically roughness discrimination capability, is a significant factor for preference and appreciation for wide range of materials, including food, furniture or fabric. In order to explore the mechanism of sensation capability through tactile senses, it is necessary to identify the relevant factors and define characteristics that dominate the process involved. The results that will be obtained under these principles will be helpful for the industry in the development and optimization of new products, especially for the individuals' with special needs. With this exploratory study we illustrate differential thresholds of tactile senses under changing conditions of surface lubrication and applied force load. Also the tests were carried out under different temperatures in order to understand the oral sensation capability. The results and correlations may provide useful information about texture sensitivity and also methodologies could be applied in general sensory studies.

1. Introduction

Surface texture, i.e. surface topography, is a significant physical property of solid materials (Quevedo & Aguilera, 2004). Surface topography is scale-dependent, visually detectable property which is more often observed through tactile senses. In engineering surface texture is predominantly characterised by the coefficient of friction and roughness attributes (Shao, Childs, Barnes, & Henson, 2010). These attributes are critically important for consumer preference and also manufacturing processes, especially for solid surfaces such as wood, glass, fabrics, etc. Similarly, during oral processing, perceived roughness is a determinative factor for liking or disliking a product.

Surface texture is explored simply by stroking the fingertip with a particular loading force across the surface of the material (Adams, et al., 2013). During these explorations, mechanoreceptors detect textural features. Bensmaia and Hollins (2003) suggested that sliding the fingertip causes vibrations that are then measured by mechanoreceptors. Sliding the finger pad on surfaces with different wavelengths may trigger different mechanoreceptors with different selective frequencies (Shao, Childs, Barnes, & Henson, 2010).

Topographical features can be assessed either by instrumental assessments (physical) or by the affective methods of sensory tests. Instrumental roughness assessment techniques can be classified as contact and non-contact methods. The former includes the profilometer measurements that operate through direct contact with the surface and scan across it. The latter methods are considered to be non-invasive and are preferred when the surface is delicate (e.g. for some food surfaces). Irrespective of the method used for an assessment, there will still be the major limitation of relating these assessments to real sensations. An ideal future plan for this scientific field would be to find a relationship between the response of consumer and the topographical properties of surfaces, which would allow consumer behaviour to be estimated without sensory testing but with a mathematical model.

Consumer perception is important for industry as it plays an important role in product preference (Barnes, Childs, Henson, & Southee, 2004; Grohmann, Spangenberg, & Sprott, 2007). Product design is a key factor in the business environment, and the design of surface texture for car interiors, furniture or packaging materials is critical for business success (Karkkainen, Piippo, & Tuominen, 2001; Trueman & Jobber, 1998). Importantly, in the market, there are alternatives for every kind of product; therefore, to move forward, it is essential to understand what customers expect and need and how to control this. Thus, the dynamics of tactile sensation and the findings related to this will be valuable for many disciplines including product design, psychophysics, neuroscience and computational modelling (Elkharraz, Thumfart, Akay, Eitzinger, & Henson, 2014).

With regard to the instrumental observations of surface topography, studies have revealed important findings. For instance, Chen, Shao, Barnes, Childs, and Henson (2009) highlighted that smooth–rough perception was related to the coefficient of friction and roughness values. Hollins, Faldowski, Rao, and Young (1993) reported that roughness–smoothness was found to be a robust dimension of touch perception and that the ‘feel’ of an object depends on a combination of perceptual properties. On this basis, roughness can be used as a measure of touch perception under certain conditions. Friction coefficient and roughness have also been claimed to have an effect on slippery–sticky, bumpy–flat and wet–dry perceptions (Hollins & Bensmaïa, 2007). These relationships illustrate that touch perception has complicated interactions with textural features and that perception is dependent on more than one physical property. Phillips and Johnson (1981) emphasised that there is some correlation between roughness and the coefficient of friction and that the oscillation amplitude applied by an individual making the assessment was found to depend on fingerprint ridges and friction coefficient (Penfield & Rasmussen, 1950; Valbo & Johansson, 1978). Based on these findings, it was planned that roughness and the coefficient of friction would be used in the present study as physical measures to understand the limits of human touch perception under different force loads, lubricated with different syrup solutions and at different temperatures.

In the present study factors, affecting the sensation of the surface topography has been investigated with the fingertip by using solid plaques that has textured surfaces. This study was exploratory rather than hypothesis-based and aimed to establish answers to the following questions:

1. What is the roughness discrimination threshold and what are the effects of lubricants with various viscosities and temperatures?
2. What is the effect of force load on the sensitivity of roughness discrimination?

2. Materials and Methods

2.1. Materials

Acrylonitrile Butadiene Styrene (ABS) plastics were purchased from a company producing car interior materials (Standex International Ltd., Cheshire, UK) and used as a sample surface in this study due to their different surface properties. These are low-cost engineering plastics that are easily processed for fabrication and were found to be ideal materials for structural applications due to their strength, stiffness and resistance to impact, chemicals and heat. Different surface textures were available, and eight surfaces were selected for this study. The main reason for using ABS plastic plaques instead of a food sample was due to the consistency within the samples.

2.1. Methods

2.1.1. Physical Assessment of the Surface Texture

2.1.1.1. R_a measurements

The first topographical physical assessment was selected to be the measurements of surface roughness (R_a). Roughness can be defined as a measure of height differences combined with the spatial properties of the surface (Bergmann Tiest & Kappers, 2006; Eck, Kaas, Mulders, & Goebel, 2013). In the literature many roughness perception studies have been reported. A review by Bergmann Tiest (2010) suggested that roughness perception has a correlation with physical surface properties such as friction, height difference and spatial pattern. The relationship between tactile perception and roughness has been tested for: cosmetic packages (Bergmann Tiest & Kappers, 2006), car crash pads (Bahn, Lee, Lee, & Yun, 2007), touch screen-printed surfaces (Childs & Henson, 2007), car interior components (Liu, Yue, Cai, Chetwynd, & Smith, 2008), wood, sandpaper and velvet (Hollins, Faldowski, Rao, & Young, 1993), linear gratings (Cascio & Sathian, 2001) and dot pattern stimuli (Dépeault, Meftah, & Chapman, 2009; Eck, Kaas, Mulders, & Goebel, 2013; Kahrimanovic, Bergmann Tiest, & Kappers, 2009).

This study measured arithmetical mean roughness R_a (μm), the integral of the deviations from the mean height of the peaks and valleys of the surface. Roughness was measured using an NPflex 3D surface metrology system (Bruker Ltd., Tuscan, USA). From this measurement a three-dimensional texture profile was generated, and post-processing software was used to obtain R_a roughness values. Measurements were done in five replicates and mean values were noted down as shown in Table 5, standard deviation values were lower than 0.001.

2.1.2. Sensory Assessment of Tactile Sensitivity and Surface Texture

2.1.2.1. Participants

A total of 62 participants (31 females and 31 males) were recruited for this study. The participants had no reported medical complications, skin problems or other known health problems that may have influenced the results of the test. The mean age was 33 ± 7 years. All sensory tests were conducted in a purpose-designed sensory laboratory within the food science and nutrition building at the University of Leeds. Ethical permission was obtained from the faculty ethical committee (MEEC 12-013), and all test procedures followed the ethical rules and regulations as set by the committee.

2.1.2.2. Test procedures

To answer the questions asked in the current study these, five different sensory tasks were planned.

Task 1. Roughness discrimination threshold: in air, water, and low, moderate and high viscosity Newtonian solutions at room temperature (25 °C).

Task 2. Roughness discrimination threshold: in water and low, moderate and high viscosity Newtonian solutions at body temperature (37 °C).

Task 3. Scoring of the sensed roughness under different conditions: in air, water and low, moderate and high viscosity Newtonian solutions at room temperature (25 °C).

Task 4. Scoring of the sensed roughness under different conditions: in water and low, moderate and high viscosity Newtonian solutions at room temperature (37 °C).

Task 5. Effect of force load on roughness sensitivity: in water and air at room temperature (25 °C).

Tasks 1 to 4 involved plaques which were submerged in different solutions so that a thin layer of lubricant was presented during the finger tactile test to investigate the effect of the lubricants' viscosity and temperature on the sensation of roughness. These findings were expected to elucidate the sensation dynamics for the skin surface when covered with a liquid (such as a moisturiser) and also to provide an indication of what could be happening inside the mouth during oral processing. Plaques were presented with three-digit blinded codes and were in a randomized balanced presentation order.

The samples were tested under the following subtasks:

1. In air.
2. In water, with the surface placed in a container with water covering the whole surface.
3. In 80 % syrup solution.
4. In 90 % syrup solution.
5. In 100 % syrup solution, as shown in Figure 1.

Syrup (Lyle's Golden Syrup Tate & Lyle, Nottinghamshire, U.K.) was used as a medium in these tasks due to its Newtonian character, displaying a constant viscosity regardless of shear rate, which might considerably vary between individuals. The solutions of 80 % and 90 % syrup were prepared by dilution with distilled water. The syrup solutions were tested for their dynamic viscosities using a Kinexus rheometer (Malvern Instruments, Ltd., Worcestershire, U.K.). The measurements were taken at 25 °C and 37 °C using cone-and-plate geometry CP2/60 (60 mm diameter and 2° angle cone). Viscosity values were constant for a wide range of shear rates, demonstrating the Newtonian nature of the golden syrup. Viscosity tests were conducted three times with samples prepared from different batches, and the mean dynamic viscosity values and standard deviations were calculated (Table 1). By using the obtained dynamic viscosity values of the solutions at 25°C and 37°C were converted into kinematic viscosity values by dividing the dynamic viscosity values into densities of the substances.

More specifically for Tasks 1 and 2 participants were asked to stroke their fingertip on the pair of plaques with a constant reference plaque to answer if they are the 'same' or 'different'. The plaques were presented in randomised order. Participants' lowest different detection was taken as individuals' threshold of roughness discrimination, which was then plotted to observe population threshold.

For Tasks 3 and 4 participants were asked to stroke their fingertip on the pair of plaques with a constant reference plaque and scale the perceived roughness in comparison with the reference, in a 0 to 9 scale. The reference plaque roughness was accepted as '0'. Obtained values for each plaque was then averaged for plotting the perceived roughness against the actual roughness value.

For task 5, roughness sensitivity versus applied force load was assessed to determine the effect of force load on sensitivity with four elected plaques (Table 2).

To define the various levels of force loading, two studies were used as reference. A study by Soneda and Nakano (2008) showed that 1 N is the optimum contact load for stimulus detection. Additionally, Adams, et al. (2013) reported that a load force up to 2 N would still be defined as a normal loading force for tactile exploration. It was therefore decided that a force between 0.8 N and 2.2 N would be categorised as a 'moderate' touch, a force up to 0.79 N classified as a 'light' touch, and a force between 2.21 N and 4 N defined as a ‘hard’ touch. The load force was measured by placing a balance underneath the test material, and the participants were trained to apply the correct range of force prior to the actual tests (Table 3).

For each task specific number of participants, aim, materials, methods, descriptions, asked sensory question and the testing temperatures have been shown in Table 1.4.

2.2. Statistical analysis

Results obtained from Tasks 1 and 2 were plotted with probit analysis to observe log-normal best fitting lines, with the confidence intervals calculated using Microsoft Office Excel 2010 (v14.0). Statistical analysis was conducted in XLSTAT (Microsoft, Mountain View, CA) and Microsoft Office Excel 2010 (v14.0).

3. Results and Discussions

3.1. Physical Assessment of Surface Texture

3.1.1. R_a Measurements

Eight surfaces were selected based on their R_a values. Calculated Ra values was shown to be different from each other ($p < 0.05$) according to the t-test carried out. Table 5 shows the surface roughness of the selected surfaces and percentage differences from the reference surface (*). This ratio was used during data analysis and presentation to demonstrate the percentage change required for sensory discrimination.

3.1.2. Sensory Assessment of Tactile Sensitivity and Surface Texture

For obtaining a threshold Just noticeable difference (JND) is a method widely used in threshold studies. It is generally accepted that half of the cumulative population response can be used as the threshold value (Chaplan, Bach, Pogrel, Chung, & Yaksh, 1994; Clark & Mehl, 1971; Laing, 1983; Meilgaard, Civille, & Carr, 2011). In line with this approach, results of Tasks 1 and 2 were plotted with probit analysis, a log-normalisation process.

For Task 1 obtained cumulative population thresholds for each subtasks has been shown in Figure 2.

These results showed that the threshold value for roughness discrimination was at a minimum when the tests were performed in air (Figure 2A). The presence of a thin layer of lubricant will lead to a reduced capability for surface discrimination. It was also found that capability for surface discrimination appeared to gradually diminish with increasing viscosity of the fluid. The JND level reached 216 % when a thin layer of highly viscous syrup was present (Figure 2E). The JND values for the different fluids are summarised in Figure 3, where JND as a percentage is plotted against fluid viscosity.

For Task 2 the obtained results were illustrated in Figure 4.

The results were similar to those observed in Task 1. JND was at its lowest when there was no fluid present between the finger and the substrate surface. The presence of a fluid layer and increasing fluid viscosity led to significantly increased JND values which also mean loss of sensitivity. These results are summarised in Figure 5.

Tasks 1 and 2 showed that the surface roughness discrimination threshold is highly dependent on the viscosity of the lubricant. The threshold value was found to increase with increasing viscosity, regardless of the temperature; there was no statistically significant difference between the sensitivities at 25 °C and 37 °C ($p > 0.05$). This indicates that the reduction of viscosity with temperature does not have a significant effect on the sensitivity, and when the JND values are compared, it can be seen that they are similar for both temperatures. This finding could be explained by the relative nature of the test in which comparisons between pairs of surfaces and set temperatures were in a range that did not affect the sensation. However, only very high or low temperatures would be expected to change the sensation as then the viscosity would be considerably changing.

A more obvious result of these findings was the reduction in sensitivity with viscosity. A possible explanation for this effect on the JND threshold is the influence of a surface-coating lubricant. A study by Ghalme, Mankar, and Bhalerao (2013) showed that the viscosity of the lubricant had a significant effect on the sensed roughness. Roughness was defined to be the integral of the deviations from the average of the peaks and valleys on a surface. Lubricants filled those peaks and valleys with different viscosities. During surface exploration with lubricants in the lower viscosity ranges (such as water or 80 % syrup), the liquid could be pushed away from those peaks and valleys, resulting in a good sensation of the actual roughness. With the higher viscosity levels (such as 90 % and 100 % syrup), pushing the solution from those peaks and valleys becomes harder, requiring a force greater than the human capability to feel the true roughness. It is worth noting that with the higher viscosities, the sensation may predominantly be due to only the viscosity of the fluid. This concept was suggested by Osborne Reynolds when he investigated the effects of lubricants on surfaces, calling this 'hydrodynamic lubrication' (Christensen & Tonder, 1971). Another supportive evidence for this theory of lubrication is the Stribeck curve.

Stribeck curve, as seen in Figure 6 is a plot of friction related to the viscosity, relative speed and load under lubrication. The vertical axis shows the coefficient of friction, and the horizontal axis combines the other variables (viscosity, relative speed of the surfaces and load on the interface). The combination of these three factors is also often referred to as the film thickness or Hersey number and it gives an indication of how close the two surfaces will be. As the horizontal axis moves, this results in increased speed and viscosity and reduced load. The Stribeck curve shows three different regimes: the boundary, mixed and hydrodynamic regimes. The boundary regime is a combination of low speed and viscosity and high load force, where friction is predominantly determined by physical contact between the two surfaces, and the bulk flow property of the lubricant does not play a role. As speed and viscosity increase or the load decreases, the mixed lubrication phase starts, and the surfaces begin to be covered by a thin film of the lubricant. During the mixed regime, the coefficient of friction is rapidly reduced as a result of decreasing surface contact and greater fluid lubrication. The coefficient of friction reaches its minimum level, and the hydrodynamic lubrication regime is initiated. At this minimum point, the load on the interface is completely supported by the lubricant, and there is almost no solid–solid contact. In the hydrodynamic regime, the two surfaces will have no physical contact but will instead be separated by a thick layer of lubricant. Increased lubricant viscosity and sliding speed and reduced surface load will all lead to an increased thickness of the lubricant layer between the two surfaces. In this case, the interaction between the surfaces will depend on the bulk flow property rather than the actual surface characteristics, so the resistance force sensed will increasingly be determined by the viscosity of the lubricant rather than by surface roughness. With regard to the Stribeck curve, it can be observed that at lower viscosity levels (i.e. water or 80 % syrup), the perceived surface topography will be due to the actual surface properties, but with increasing viscosity (90 % or 100 % syrup), the sensation will be determined by bulk flow behaviour rather than by the surface itself. This suggests that the results from tasks 1 and 2 can be supported with the evidence of the hydrodynamic lubrication theory.

The results of Task 3, which was designed to understand the perceived roughness under different viscosities at room temperature, was plotted in Figure 7 as mean values of obtained scores.

These results demonstrated that the sensation of the surface roughness was weakened by the presence of a fluid layer between the substrate surface and the skin. The perceived roughness showed good correlation with the actual surface roughness at each concentration ($p < 0.05$). However, this correlation became rather less discriminating (smaller slope) when a layer of syrup was present during the test (Figure 7).

For Task 4, same test procedures as in Task 3 was repeated at body temperature (37 °C). The results were obtained by calculating the mean scores and are shown in Figure 8.

As with task 3, the perceived roughness showed a good correlation with the actual roughness ($p < 0.05$), which was rather flattened by increasing the viscosity of the lubricant.

The results of Tasks 3 and 4 were not significantly different, i.e. temperature did not have a significant effect on the perceived roughness ($p > 0.05$). These findings clearly showed that the perception of roughness is dependent on properties of the lubricant. Moreover, as previously mentioned, the Stribeck curve is a clear evidence to certain finding of the lubricant viscosity of the sensation aspect. It can therefore be claimed that with lubricants with lower viscosities, perception is mainly determined by the actual surface characteristics but that when the lubricant's viscosity increases, then the lubricant moves into the hydrodynamic regime, and the sensed roughness is then mainly dependent on the bulk flow properties of the lubricant rather than the actual surface topography.

Task 5, focused on the effect of force load on the roughness perception. The participants were asked to choose the rougher/smoother surface, and the ranking tests were analysed based on their selection. The results were analysed using the method of Meilgaard, Civille, and Carr (2011) and are presented in Table 6.

Each participant made 36 judgements in pairwise comparisons. The resulting scales showed that the participants were not able to discriminate surfaces A and B using a light touch. Notably, the participants' capability to discriminate surfaces was reduced in water. More interesting findings were obtained when the correct/incorrect identification was counted for the rougher/smoother surface, with a clearly poorer surface discrimination capability in the presence of water, as shown in Figure 9.

It is clear from these graphs that the probability of making an error during the selection of the rougher/smoother surface under certain force levels significantly decreased with increased force ($p < 0.001$). It can therefore be concluded that increasing the force load increased sensitivity but that there was no significant difference between the sensitivities at the moderate and higher levels of force.

A possible reason for this finding was suggested as the increased contact area of the fingertip under an increased load. This hypothesis was investigated by measuring the fingertip contact area for 6 people (3 females and 3 males) while applying different ranges of forces. The selected participants were asked to press their fingertip on the inkpad and then apply a force on the graph paper placed on top of the scale (Table 7). The fingertip area was calculated by visually counting of the boxes and was plotted against the force load as shown in Figure 10.

This graph shows that the fingertip contact area with the substrate increases with increased force load. Assuming that the skin has a constant density of mechanoreceptors, an increased contact area would mean a large increase in the number of mechanoreceptors involved in surface texture detection, which would certainly assist in the correct recognition and assessment of surface roughness.

4. Implications for Roughness Sensation during Oral Processing

The results of the fingertip roughness sensation tasks provide an opportunity for estimating oral conditions. Previous findings reported by Aktar, Chen, Ettelaie, and Holmes (2015a) and Aktar, Chen, Ettelaie, and Holmes (2015b) for elasticity and firmness perception, in particular, have shown that the tongue and fingertip have similar discrimination sensitivities, whereas for viscosity tongue showing a slightly higher sensitivity. On the other hand, tactile sensation tests (touch sensitivity and 2PD tests) have demonstrated that the tongue having a slightly higher sensitivity. These findings suggest that textural results obtained only by fingertip assessments could give a prediction of oral conditions, while noting that the tongue could have a slightly higher sensitivity. Noteworthy in order to make a concrete statement about the tongue sensitivity, the saliva contribution during the sensory tests is necessary. Furthermore, in this study, the effect of temperature was also tested (at body temperature and room temperature) and was found to be negligible, at least for roughness perception. Therefore, the results obtained in this study could be used for estimating oral roughness sensation under different conditions.Given this, with food scientists point of view, it is possible that roughness sensation in the mouth would be reduced with a surface coating such as gravy sauce, honey. If a food producer aims to mask roughness, then it would be reasonable to use a high viscosity medium to cover the surface, which would reduce the sensation of roughness during oral processing. However, as mentioned before obtained results are still an estimation for the mechanism of oral sensation, until a study shows the sensation dynamics under the effect of saliva contribution. The results of the present study also showed that higher force loads increase the sensation of roughness. This can be applied to oral processing by claiming that increased oral forces (i.e. tongue pressure) may increase the sensation of roughness. A consumer could therefore increase or decrease the force load during oral processing according to whether they wanted or did not want to sense the roughness. It should be noted that these statements are an estimation based on the experimental findings and that oral processing is a much more complicated procedure than fingertip roughness sensation. In this area, further investigations are necessary to confirm or contradict our findings.

5. Limitations

While the findings of these experiments are significant, there were some noted limitations worth discussing. The experiments were performed using surfaces that had been designed as car crash pad patterns for interior car materials. They were selected due to their good durability under certain conditions such as in heat or water. However, for threshold tests using JND, investigators are advised to use samples that have similar differences. In the present study, the materials were not produced with this aim; therefore, the given threshold values should be considered to be ranges rather than exact values, due to unavailability of an alternative.

Also, the lubricants used in this study were as chosen due to their different viscosities, and the densities of the selected solutions according to their test temperatures were encountered into results by calculating the kinematic viscosities.

Additionally, during the assessment of the force load on sensitivity (Task 5), a balance was used to control the force applied by the participants. Even though the participants were trained prior to the tests, it was not possible to apply a single constant force throughout the surface exploration. To minimise this load force fluctuation, wide ranges of force were defined.

6. Conclusion

These sets of tests were conducted to observe the participants' sensitivity in discriminating surface textures under different conditions. A number of textured plaques originally produced as a car crash pad were used in this study.

The results showed that increasing the viscosity of surface lubricants reduced the sensitivity of roughness perception. This finding was supported by the lubrication theory as shown using the Stribeck curve.

These experiments were repeated for two different temperatures: room temperature and body temperature. The main motivation for this was to predict the perceived roughness during oral processing. The previous experiments reported in Aktar, Chen, Ettelaie, and Holmes (2015a) and Aktar, Chen, Ettelaie, and Holmes (2015b) showed that the tongue and fingertip had similar texture discrimination capabilities, and this was used as evidence to support using fingertip assessments for estimating the oral conditions for roughness. It should be noted that such estimation of the tongue's roughness sensation is not supported by concrete evidence but can only be used as an estimate.

Another aspect of this study was to observe whether or not different wavelengths of sliding the fingertip over the surfaces would stimulate a better subjective assessment of texture. To investigate this, the sensitivity of roughness–smoothness perception was tested for a variety of load forces on the textured surfaces with a set of ranking tests. It has been claimed that during texture perception, the amount of force load is adjusted according to the topography of the surface, which could prevent individuals from applying very high forces on soft surfaces, such as squeezing a piece of cake (Adams, et al., 2013; Phillips & Johnson, 1981). In the present study, the surfaces used had similar topographical properties to avoid the natural limitation of force loading (Skedung, et al., 2011). The participants were trained before the experiments to apply the specified force load levels, and each participant was successful at controlling their force load within a given range. The results of the ranking tests (Taks 5) showed that the probability of mistakes in choosing the rougher/smoother surface decreased with increasing force loads. This was supported by the measurements of fingertip contact area for different force loads, which showed that the area of the fingertip increased with increasing force. This could mean that the density of the mechanoreceptors also increased, thereby reducing errors in rougher/smoother selection. The findings of the present study also indicate that water does not result in a dramatic change in roughness sensation. However, when different surface coatings were used, i.e. different concentrations of syrup solution, these resulted in significantly reduced threshold levels with increasing viscosity values.

Ethical Statements

The authors declare that they do not have any conflict of interest. Ethical permission of this study was approved by the ethical committee of the University of Leeds (MEEC 12-013), and all test procedures followed the ethical rules and regulations as set by the committee. Panellists who agreed to take part in this study were informed and signed the consent forms.

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Figure 1. Sensory test conditions using different lubricants at a certain temperature.

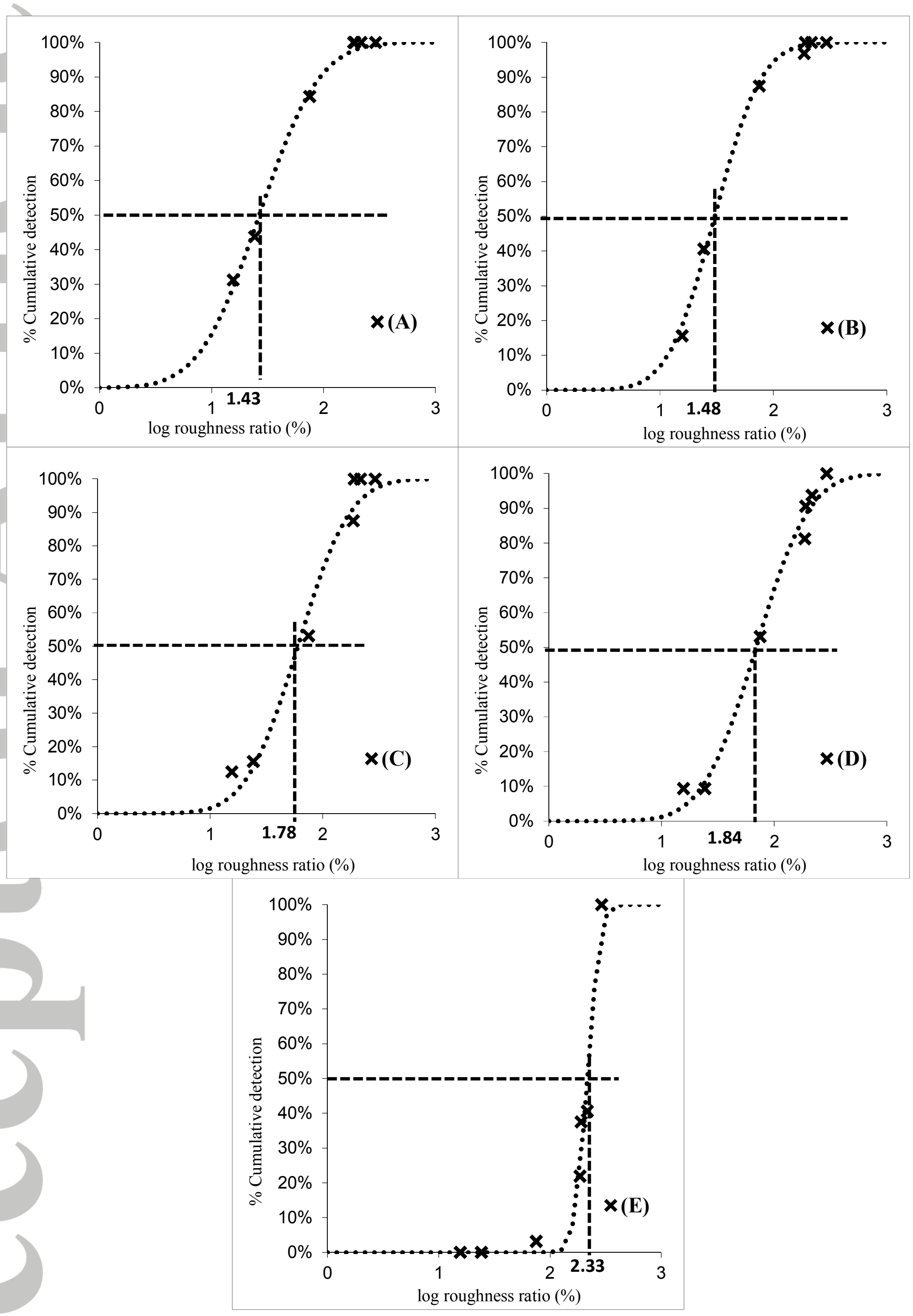


Figure 2. Log-normal fitting (probit analysis) of the cumulative population percentage vs the roughness ratio at room temperature (25 °C) for: (A) in air (Median: $10^{1.43}$ = 29 %), (B) in water (Median: $10^{1.48}$ = 30 %), (C) in 80 % syrup (Median: $10^{1.78}$ = 60 %), (D) in 90 % syrup (Median: $10^{1.84}$ = 63 %), and (E) in 100 % syrup (Median: $10^{2.33}$= 216 %).

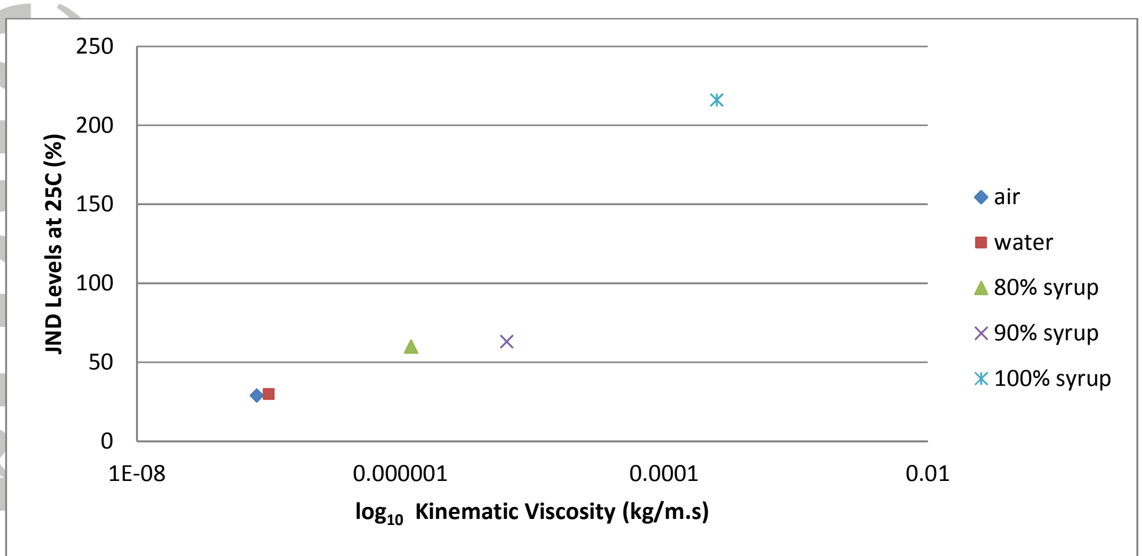


Figure 3. Obtained JND levels of the roughness discrimination for different kinematic viscosities in logarithmic scale of viscosity at 25 °C.

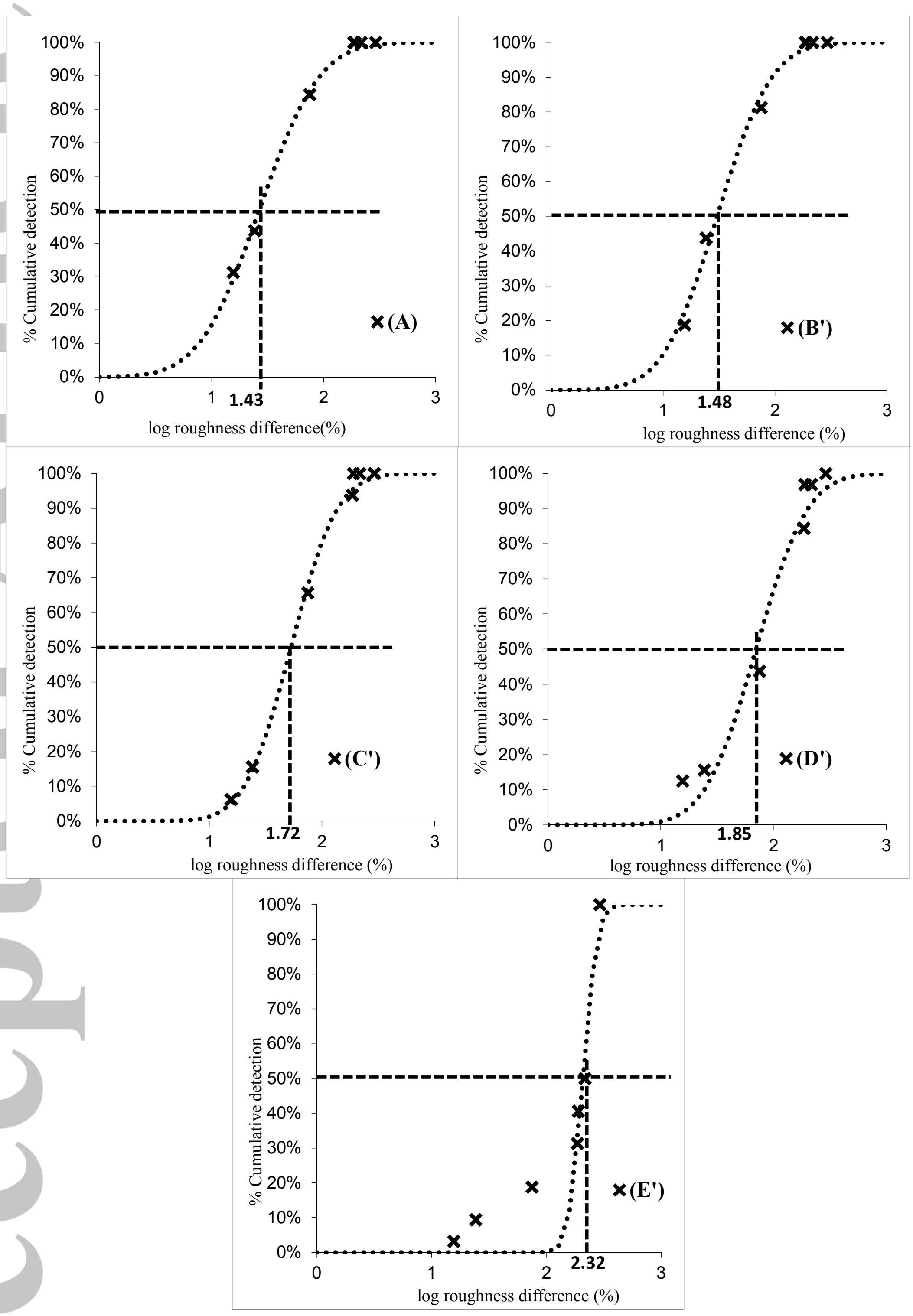


Figure 4. Log-normal fitting (probit analysis) of the cumulative population percentage vs the roughness ratio at 37 °C for B', C', D' and E' and 25 °C for A, for (A) in air (Median: $10^{1.43}$ = 29 %), (B') in water (Median: $10^{1.48}$ = 30 %), (C') in 80 % syrup (Median: $10^{1.72}$ = 53 %), (D') in 90 % syrup (Median: $10^{1.85}$ = 70 %), and (E') in 100 % syrup (Median: $10^{2.32}$= 207 %).

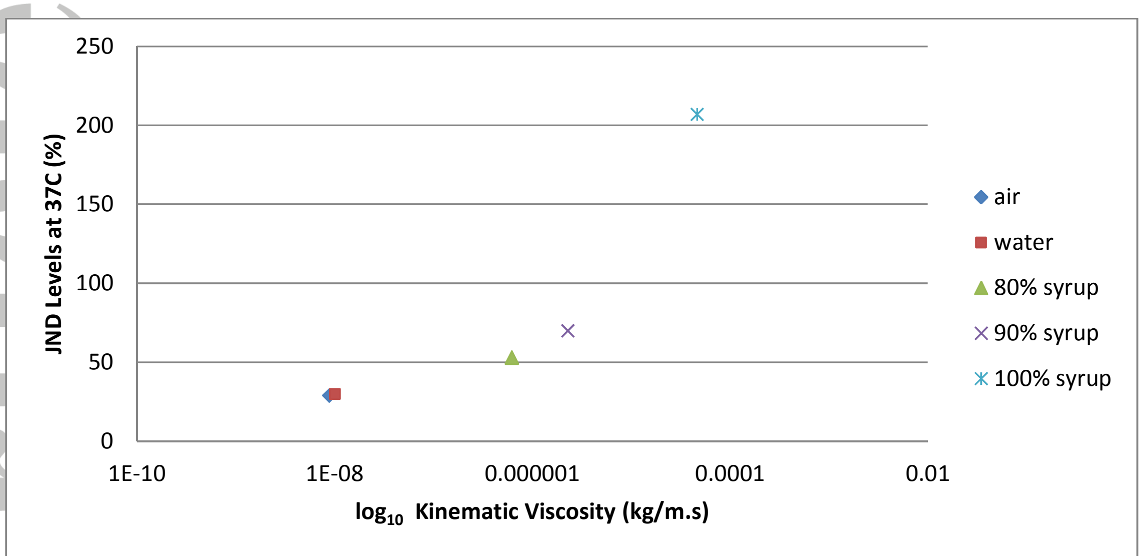


Figure 5. Obtained JND levels of the roughness discrimination with different kinematic viscosity levels in logarithmic scale at 37 °C.

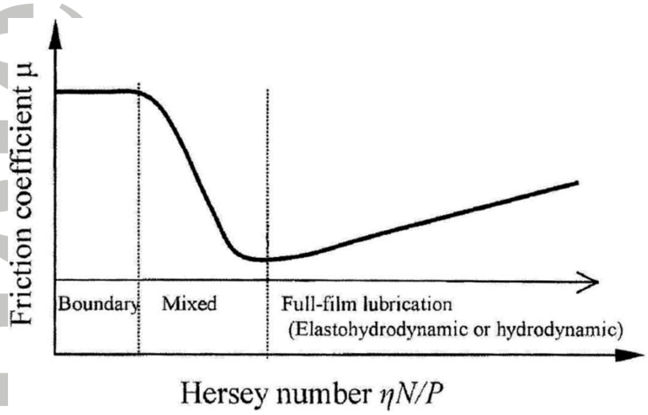


Figure 6. Stribeck curve, showing the friction coefficient against the Hersey number with three different regimes, boundary, mixed and full-film lubrication (Woydt & Wäsche, 2010). Horizontal axis is the *ηN/P*, where *η* stands for viscosity, *N* relative speed of the surfaces and *P* as the load on the interface per unit.

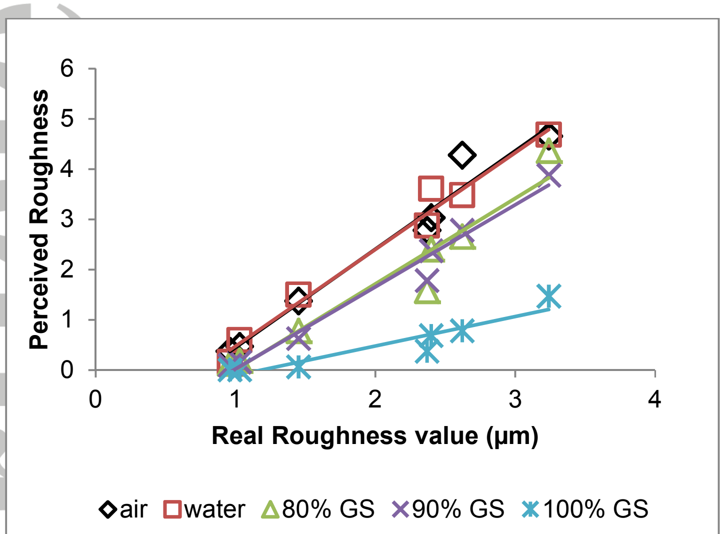


Figure 7. Average scores of the roughness values against the real roughness value for the different conditions of air, water, 80 % syrup, 90 % syrup and 100 % syrup, at 25 °C.

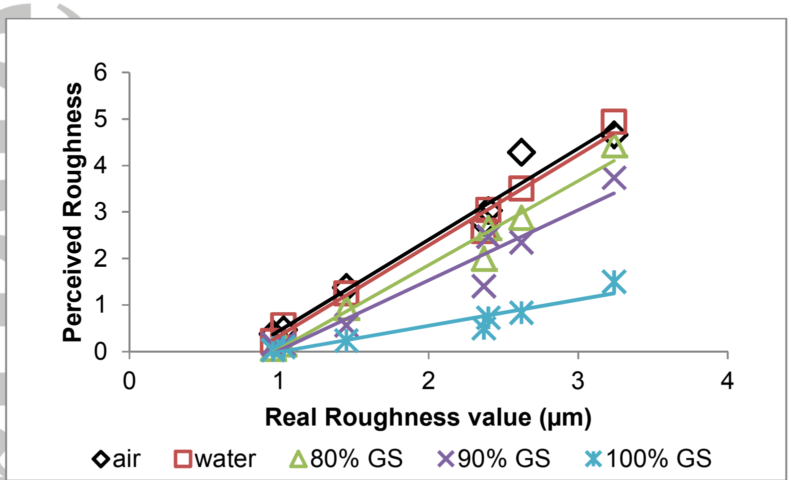


Figure 8. Average scores of the roughness values against the real roughness value for the different conditions of air, water, 80 % syrup, 90 % syrup and 100 % syrup at 37 °C.

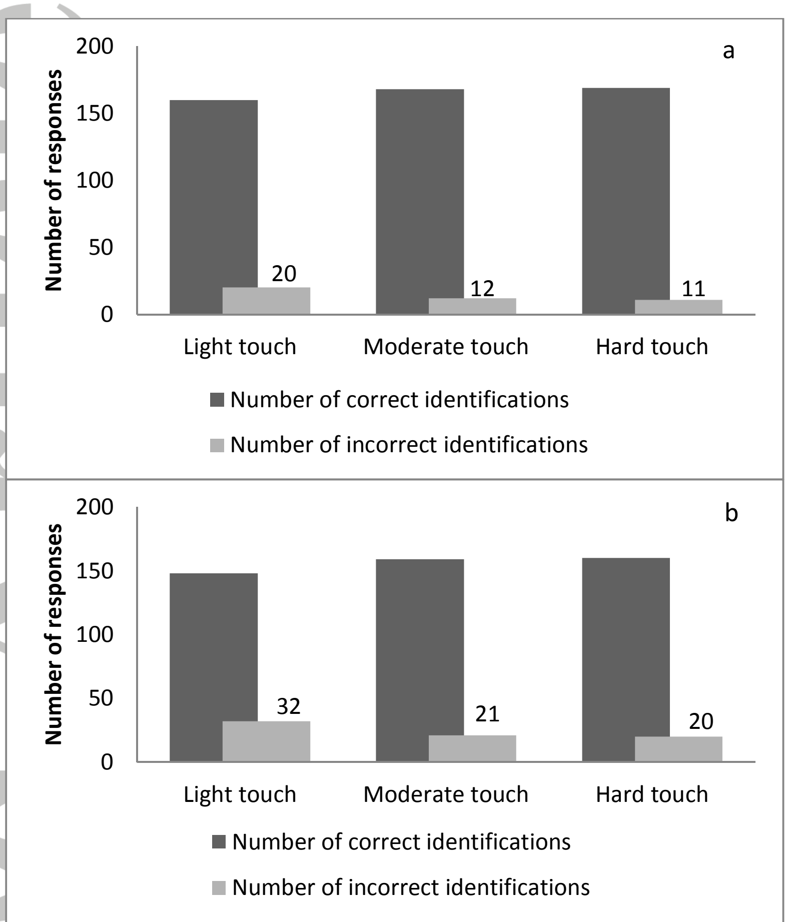


Figure 9. Number of correct/incorrect identification during the ranking tests done for observing the surface texture properties with three different force ranges at room temperature, in air (a) and, in water (b).

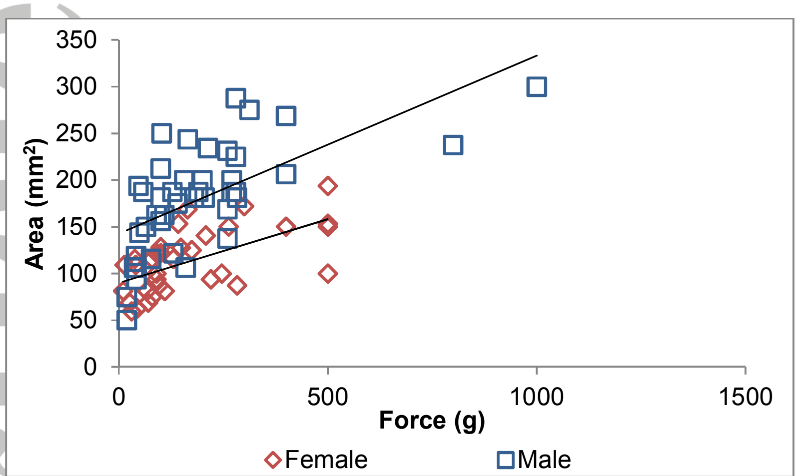


Figure 10. Area of the fingertip during different force loads applied for female and male subjects.

Table 1. Viscosity values of the syrup solutions at different temperatures including the standard deviation of the replicates.

Classifications of the solutions	Solution	Viscosity ± Standard deviation (Pa.s)	Calculated kinematic viscosity (kg/m.s)
Low viscosity	80 % syrup (25 °C)	0.16 ± 0.02	$1,2.10^{-4}$
	80 % syrup (37 °C)	0.07 ± 0.02	$0,62.10^{-4}$
Moderate viscosity	90 % syrup (25 °C)	0.88 ± 0.02	$6,4.10^{-4}$
	90 % syrup (37 °C)	0.29 ± 0.01	$2,2.10^{-4}$
High viscosity	100 % syrup (25 °C)	34.6 ± 1.5	$2,5.10^{-2}$
	100 % syrup (37 °C)	6.54 ± 0.29	$0,46.10^{-2}$

Table 2. Actual roughness values for the selected surfaces for pair-wise ranking test.

Surface number	Roughness (μm)
A	0.96
B	1.03
C	1.45
D	2.37

Table 3. Descriptions of force ranges given to the participants.

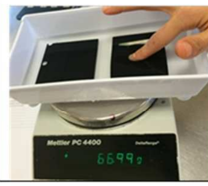
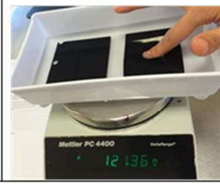
Force load, F_L (g)	$79 < F_L$	$80 < F_L < 220$	$221 < F_L < 400$
Inside air at 25°C			
Inside water at 25°C			

Table 4. Details of the sensory assessment tasks applied in the current study.

	Task 1	Task 2	Task 3	Task 4	Task 5
Number of participants	32, (16 female, 16 male)				30, (16 female, 14 male)
Aim	To investigate the roughness discrimination threshold using lubricants with different viscosity and temperature.		To investigate the perceived roughness using lubricants with different viscosity and temperature.		To investigate the importance of force load on the surface roughness discrimination capability.
Material	8 different ABS plaques (1 reference, 7 test sample) (Table 5).				4 different ABS plaques (Table 2).
Methods	Pair-wise comparison of the constant reference plaque and sample plaques.				Pair-wise ranking with 2 alternative forced choice (2AFC) (Meilgaard, Civille, & Carr, 2011). Plaques were compared with pairs in all possible permutations (6 comparisons per force load range).
Descriptions	Plaques were submerged in the lubricant and panellists were asked to slide their fingertip on the surface in order to sense the surface roughness.				Force load levels were divided in three different levels: light, moderate and hard touch. Loading force was controlled with a balance placed underneath the surfaces (Table 3).
Sensory Question	‘Are they the same or different in terms of surface roughness?’		‘What would you scale of the test plaques roughness on a scale of 0 to 9, where reference plaque has the value of 0?’		‘Within the described force range, explore the surface roughness of presented two surfaces and select the rougher/smoother plaque.’
Sub-tasks	1. In air. 2. In water. 3. In 80 % syrup solution. 4. In 90 % syrup solution. 5. In 100 % syrup solution.		1. In air. 2. In water. 3. In 80 % syrup solution. 4. In 90 % syrup solution. 5. In 100 % syrup solution.		For each force range: 1. In air. 2. In water.
Test temperature (°C)	25	37	25	37	25

Table 5. Actual roughness values of the plaques, with the calculation steps of the % roughness ratio (* indicates the reference value) (R_a indicates roughness value, where R_a* indicates the roughness of the reference plaque).

Surface number	Roughness (μm)	Difference from the reference (μm)	Difference ratio	% Difference ratio
		$Ra - Ra*$	$\frac{Ra - Ra*}{Ra*}$	$\frac{Ra - Ra*}{Ra*}\ x\ 100$
1*	0.83	0	0	0
2	0.96	0.13	0.16	16
3	1.03	0.20	0.24	24
4	1.45	0.62	0.75	75
5	2.37	1.54	1.86	186
6	2.40	1.51	1.90	190
7	2.62	1.79	2.16	216
8	3.24	2.41	2.91	291

Table 6. Actual roughness scale and observed scales by ranking test for the test in air and inside water at room temperature for 3 force ranges, light, moderate and hard touch. The results were converted to percentage values.

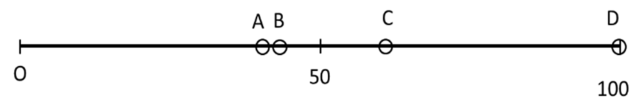
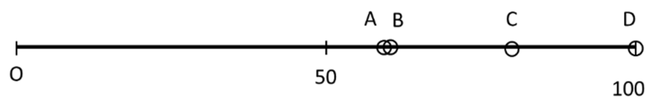
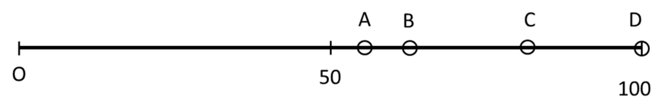
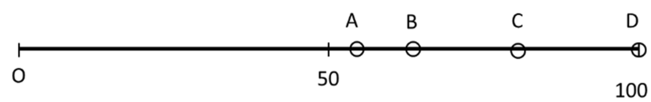
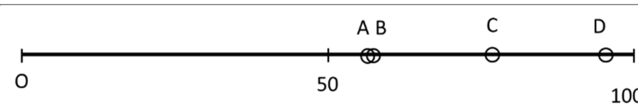
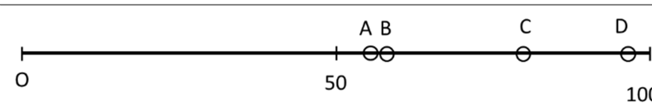
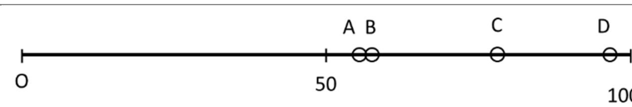
Actual roughness scale (physical)	
	
Testing of roughness in under normal conditions 'air'	
Force range	Observed scale
Light touch	
Moderate touch	
Hard touch	
Testing of roughness inside water (25 °C)	
Force range	Observed scale
Light touch	
Moderate touch	
Hard touch	

Table 7. Actual fingertip prints, which were printed on a graph paper (after pressing the fingertip on inkpad) with controlled force loads (on the scale). Each fingertip was coded and the force was noted for calculation.