Packaging

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Laboratory measurement method for the mechanical interaction between a tactile sensor and a cartonboard package – presentation and evaluation

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Abstract: The importance of sensory information in product purchasing decisions has gained increasing attention in recent years. Tactile properties of packaging are usually measured with the help of trained evaluators. An objective, fast and repeatable method that describes the mechanical interaction and does not rely on a panel would have many benefits. We propose and evaluate such a method for measuring the mechanical interaction between a deformable finger-like shaped sensor and a package. Evaluation of the method shows good repeatability, the variability in the measurement result is within a few percent in most cases. The method captures indentation differences at contact between sensor and package due to measurement position and package design.

Keywords: grip sense; grip stiffness; laboratory measurement method; package deformation; tactile sensation.

Introduction

Packaging is increasingly becoming regarded as an integrated part of the offering of a product (Löfgren 2005). Engaging all the senses of a customer can deepen the connection to the product (Krishna et al. 2017) and this has been extended to packaging with the concept of *multisensory packaging* (Petit et al. 2019). Because of that, the tactile sensation of packaging has become a topic of interest for research and industry, see e. g. (Chen et al. 2009, Rundh 2013).

In the multisensory customer journey, there is a clear ordering of when in the process different senses come into

play. Visual information, and to a lesser degree auditory and olfactory, can draw attention to the product and make a consumer consider it for purchase. Haptic information in contrast is only available at a later stage, when the consumer has decided to interact with the product to learn more about it and hopefully confirm expectations (Krishna et al. 2017). Despite the later entry of haptic information, it is nevertheless a crucial part of the customer experience. The consumer's perception of the product and brand will be influenced by e. g. mechanical interaction between the finger and the package (Peck and Childers 2003). This applies in the store when contemplating a purchase, but also when the product is used, as long as the original packaging remains as the container of the product, what Löfgren calls the *first and second moments of truth* (Löfgren 2005).

Producers and designers of packaging need to be aware of how design and manufacturing steps influence mechanical interaction when the packaging reaches the consumers. All the steps in the packaging value chain have an influence; from material production, converting method, filling, transport, to sale. Therefore, any method for testing the packaging needs to be flexible enough to be used at different stages in the value chain.

Compression tests with distributed load are used to measure risks for transport damages due to e. g. stacking and transportation (Ristinmaa et al. 2012). Mechanical interaction has also been measured with different compression tester methods (Andreasson and Bengtsson 2002, Ahltaainen 2009, Eriksson and Korin 2017).

Eriksson and Korin mounted rigid spherical indenters in a uni-axial testing machine. Their study showed that the radius of the sphere influences the measured stiffness. They concluded that the rigid indenter interacts mechanically differently with the package than a deformable finger does. Thus, the geometry and deformation of the human finger that executes the force influences the local mechanical interaction.

A way of evaluating the mechanical interaction has traditionally been measuring the tactile attributes of packaging by manual testing according to the standard ISO 8587:2006 (ISO 2006), i. e. a psychophysical ranking test.

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When testing according to the standard, subjects take the packages and make subjective assessments of the tactile sensation. The test thus requires a well-trained test panel and is hence expensive and time consuming.

A mechanical laboratory method presents several benefits over human test panels. It makes the measurements objective and repeatable, based on physical variables that can be influenced in process control. It also makes it possible to communicate requirements between actors in the value chain.

Other information during mechanical testing that cannot be obtained with a stiff ball can be gathered by using a deformable artificial finger with several measurement positions in the finger, e. g. the BioTac from Syntouch Inc. (Wettels et al. 2008). This method gives more information and allows tests in the laboratory of the local mechanical interaction between the package and the sensor. Previous studies show that this type of finger-like tactile sensor can distinguish different materials and geometries (Su et al. 2012, Eriksson et al. 2020).

The aim of this article is to present a method that is objective, repeatable and easy to apply for measuring the mechanical interaction between an artificial fingertip and a cartonboard package. The method is here presented and evaluated by studying repeatability and correlation with package design. Previous work has shown the potential of this method to describe the mechanical interaction. To make the measurement method more precise, the application of force and the rate of displacement should be controlled. Therefore, the finger-like sensor is in this method mounted in a uni-axial testing machine.

Materials and methods

We present here a detailed description of the general method we devise to measure the mechanical interaction between a finger-like sensor and a cartonboard package. The specific settings for this study, i. e. the equipment and setup used in this work, are presented along with the experiments done to validate the repeatability of the method and the results dependence on position.

Laboratory measurement method

To measure the loading on the finger when in contact with a package a finger-like (BioTac) sensor is mounted in a uni-axial testing machine, see Figure 1. With the uniaxial tester the total load and displacement is measured.

The following procedure is used:

Figure 1: Biotac mounted in the uni-axial tensile tester. A: SPI device, secure with double-sided adhesive tape. B: 500 N load cell. C: Custom made fixture. D: BioTac. E: Fixed plate.

1. Let the samples acclimatize in a controlled climate, same as the testing climate, for at least 24 hours, then erect the cartons and let them rest for another 72 hours.
2. Install the sample and set the measurement position.
3. Start the uni-axial testing machine and reset the load cell and the zero of deformation
4. Set up the program of the tensile tester, including:
 - a. Constant speed of displacement
 - b. The desired stop point, usually a fixed displacement.
 - c. Return to zero after the stop point.
 - d. Automatic stop at 45 N to avoid damaging the sensor in case of accidentally running into a hard object.
5. Start the sensor logging software and check the live data feed for any signs of loose connections or other sources of error that could influence the results. Then start the recording of data. The sensor should be connected and running for at least 10 minutes before the test to allow the temperature to equilibrate.
6. Start the compression testing program and let it run to conclusion. Then stop the logging of the sensor and save the results.
7. Synchronize the data from the finger-like sensor with the data from the tensile tester. This can be automated by correlating the signals around the first contact.

During a test, the uni-axial testing machine moves the upper beam down at constant speed and records the reaction force as well as the displacement. When the upper beam moves downwards and the BioTac encounters the package, the package deforms. Due to the fluid in BioTac and the elastic skin, there will be a fluid transport in the sensor, which influences the electrode measurement results. There will be a continuous loading until the test is ended.

We recommend and used a 10 min warmup of the BioTac to let its temperature reach equilibrium and minimize drift, see BioTac manual (Fishel et al. 2015). The on-board processing of the BioTac produces heat when the BioTac is running and the resistance in the voltage dividers used to collect data changes with temperature, so there is likely to be drift in the first minutes as the BioTac warms up. A constant speed of 60 mm/min was set for the tensile test and a stop point of 10 mm displacement. The measurements taken by the BioTac and the testing machine were synchronized by maximizing the correlation between the force and the pressure signal around the first contact between the BioTac and the carton.

Since the signal cable from the BioTac passes over the load cell, care was taken to keep its position fixed, i. e. the force in the cable constant, to ensure its influence could be discounted. To achieve this, the cable was supported firmly on both sides of the load cell and whenever the cable was touched it was left to relax before any measurement were taken to avoid changes in the force across the cable.

Studied evaluation cases

To get an understanding for the ability of the method to distinguish two relatively similar cases, two different sensor positions were tested but with same package material and package geometry. To reduce the effect of unintentional drift in how the procedure was carried out, the two load cases were mixed in an alternating sequence. Measurements were performed at positions (A) and (B), see Figure 2. The difference between these two cases is small, while still likely to be of the type that would influence the mechanical interaction between the finger-like sensor and the package.

Materials used

Finger-like sensor

The finger-like BioTac sensor consists of an epoxy core with built-in sensor electrodes, see Figure 3. A silicone

Figure 2: Position of the measurement of the package. The measurement is performed with first point of contact 10 mm from MD-crease. Position A is in the middle of the longest side (55 mm from the insert tab). Position B is 35 mm from the insert tab.

Figure 3: (a) The BioTac sensor. (b) The positions of the electrodes within the sensor with the sensor seen from above, nail on the upper side.

elastomeric skin filled with a conductive fluid encloses the core. The core, the fluid and the skin mimic the bone, the soft pulp and the skin of the human finger, respectively. When the sensor is pressed against a surface, the fluid is displaced. This is picked up as a change in impedance

Figure 4: Schematic illustration of how the BioTac sensor works, the electrodes give result based on indentation at the electrode position. To the left, (a) the sensor is un-affected and to the right, (b) the sensor is pressed against the object.

measured between the 19 electrodes embedded in the core and four reference electrodes. The position of the electrodes with the fingernail pointing up from the paper are shown in Figure 3 (b). In addition, the BioTac has a pressure transducer that measures the total pressure in the fluid. The pressure signal is low-pass filtered and digitized to a 12-bit signal at a resolution of 36.5 Pa/bit (Fishel et al. 2015).

When the sensor is pressed against a surface, the distance between the core and the elastomeric skin changes, see Figure 4. During compression, the fluid is displaced and the available area for the current to pass through diminishes which increases the impedance. The approximate relationship between impedance and the digitized 12-bit signal is:

$$Z_i = \left(\frac{4095}{E_i} - 1 \right) 10k\Omega, \quad (1)$$

where Z_i is the impedance measured over the i th electrode and E_i is the raw bit value of the i th electrode (Fishel et al. 2015). This means that a decreasing bit value of an electrode should be interpreted as fluid being displaced from the vicinity of that electrode, raising the impedance, while

Table 1: Specification data for BillerudKorsnäs White 290.

Property	Method	Nominal value	Tolerance
Basis weight	ISO 536	290 g/m ²	±5 %
Caliper	ISO 534	420 μm	±6 %
Bending resistance			
L&W 15° MD	ISO 2493	430 mN	−15 %
L&W 15° CD	ISO 2493	230 mN	−15 %

an increased value implies that more fluid has moved to the vicinity of the electrode.

In this study all values have been normalized so that the electrode levels at rest, i.e. before contact with the package, are all set to zero. This compensates for any individual differences between BioTac sensors and the inflation of the BioTac, since manually replacing the skin and refilling the BioTac is part of the user service program.

The above cited relationships between physical units and BioTac values should be viewed as guidance to interpreting the bit values presented in the results section. As recommended in the product manual, we use the raw bit values directly rather than first converting them to physical units.

Uni-axial testing machine

A uni-axial testing machine, Lloyd LR5K (Lloyd Instruments, Fareham, UK), fitted with a 500 N load cell, was used to cause a controlled deformation and deformation speed on the package. The procedure is repeated the same way each time. The uni-axial testing machine measures the force and deformation while BioTac measures the total pressure and the impedance at 19 electrodes as described earlier.

Packages of cartonboard material

The cartonboard used, BillerudKorsnäs White 290, is a 4-ply board built up as a sandwich construction with clay coating layers on each side. The top and bottom layers consist of bleached sulphate pulp and the core consists of two middle plies, based on a mixture of bleached CTMP and bleached sulphate pulp.

The material properties of the packages in this study follow specifications according to Table 1.

Packages, ECMA A20.20.03.01, were industrially converted from a single roll of BillerudKorsnäs White 290. The

Figure 5: Cutout sketch of the studied package, ECMA type A20.20.03.01. Measurements were $A = 78$ mm, $B = 50$ mm, $H = 110$ mm, $F = 32$ mm. MD and CD denote the machine and cross direction, respectively.

drawing dimensions on the package were $78 \times 50 \times 110$ mm, see Figure 5.

Finite element analysis

To illustrate package panel deformation, in discussion of the laboratory measurement results, a simplified Finite element Analysis (FEA) was done in Abaqus 2019 with a rigid table and rigid spherical indenter (radius 8,75 mm). The only allowed deformation was in the package.

The package was made up as one single part using the extruded shell feature. Flaps were made using the planar shell feature. The material was built up with a 4-ply cartonboard material, modelled with an elastic-plastic continuum model with a Hill yield surface and isotropic hardening. The material data and Hill criterion was used the same as used by Hallbäck et al. (2014).

The package mesh was continuum shells using S4R elements, with reduced integration, hourglass control and finite membrane strains. The package simulated in position B had element type SR4, 20,809 linear quadrilateral elements and number of nodes 21,062, free meshing (advancing front).

The mesh was seeded with an approximate global seed of 2.0 with a curvature control of 0.04. Edge seeds had

Figure 6: Force-deformation curve for load case A and load case B.

an approximate size of 0.9 and 0.7 with a curvature control of 0.04. Edge seeds were used close to the point of contact. The package dimension was the same as in the laboratory experiment. No creases were modelled in this analysis.

Abaqus general contact algorithm was used throughout the analysis. Normal behavior with default settings and tangential behavior with a penalty friction formulation with a friction coefficient of 0.5.

The rigid table was constrained in all degrees of freedom. The rigid indenter was initially placed 0.1 mm above the point of contact. A displacement boundary condition was placed on a reference point that was situated in the center of the top surface of the indenter. The indenter was only allowed to move in the normal direction of the panel. During the analysis the indenter travelled 6.6 mm vertically downwards. The step time was 1 second.

Results and discussion

Characteristic load results from measurements at positions A and B are shown in Figure 6. Damage is unlikely to be the property that affects the mechanical interaction in the first and second moment of truth (Martin Löfgren 2005). Therefore, the focus should be on the ascending part of the load curves up to maximum peak load. It is clear from this result that distinguishing these two load cases purely based on the force/displacement behavior is exceedingly difficult without applying excessive force to

Table 2: Mean and standard deviation of electrode values at different load levels and load cases.

Electrode	Load case A			Load case B		
	5 N	10 N	15 N	5 N	10 N	15 N
Pdc	544 ± 5.2	728 ± 5.2	834 ± 6.3	542 ± 4.1	711 ± 3.4	807 ± 4.9
E01	103 ± 7.8	125 ± 6.9	143 ± 6.1	112 ± 5.3	131 ± 6.3	146 ± 6.6
E02	-22 ± 2.7	-54 ± 2.8	-71 ± 2.8	-17 ± 1.4	-47 ± 2.3	-63 ± 2.4
E03	22 ± 1.4	10 ± 1.8	-8 ± 2.4	26 ± 0.9	18 ± 1.5	6 ± 1.9
E04	115 ± 2.5	149 ± 1.7	162 ± 1.6	120 ± 2.1	155 ± 2.0	168 ± 2.0
E05	56 ± 1.1	61 ± 1.3	53 ± 1.7	60 ± 1.0	67 ± 1.4	64 ± 1.6
E06	139 ± 2.3	195 ± 2.0	219 ± 1.6	144 ± 2.4	197 ± 2.8	222 ± 2.7
E07	-144 ± 4.0	-259 ± 6.6	-297 ± 6.4	-158 ± 3.6	-298 ± 8.9	-356 ± 10
E08	-180 ± 5.6	-347 ± 7.0	-420 ± 7.8	-193 ± 3.8	-398 ± 8.9	-517 ± 13
E09	-179 ± 4.7	-353 ± 5.4	-428 ± 6.2	-201 ± 6.0	-415 ± 8.5	-520 ± 10
E10	-300 ± 8.9	-682 ± 9.0	-867 ± 12	-325 ± 7.9	-776 ± 13	-1042 ± 20
E11	141 ± 6.4	143 ± 5.5	155 ± 5.3	125 ± 4.2	118 ± 4.6	126 ± 4.7
E12	-23 ± 2.0	-73 ± 1.8	-99 ± 2.3	-28 ± 2.1	-80 ± 2.2	-106 ± 2.6
E13	20 ± 1.3	-5 ± 1.4	-32 ± 2.2	19 ± 1.3	-4 ± 1.7	-28 ± 2.9
E14	103 ± 3.1	120 ± 2.6	126 ± 2.3	100 ± 1.9	115 ± 2.7	121 ± 2.6
E15	50 ± 1.8	47 ± 2.0	32 ± 2.4	50 ± 1.3	47 ± 2.2	37 ± 2.7
E16	123 ± 4.1	157 ± 4.1	172 ± 4.0	119 ± 2.7	151 ± 4.1	164 ± 4.2
E17	-338 ± 15	-1799 ± 63	-3335 ± 17	-340 ± 10	-1679 ± 68	-3259 ± 29
E18	25 ± 1.0	-15 ± 2.6	-103 ± 7.3	28 ± 1.0	-1 ± 1.9	-56 ± 5.6
E19	61 ± 1.4	63 ± 2.9	50 ± 4.8	63 ± 1.4	67 ± 3.1	59 ± 4.5

what a consumer is likely to do. Additional information will be required to reliably distinguish these load cases.

In total, 26 packages were tested in position A and 25 packages in position B. The measurement results with average values and standard deviations are shown in Figure 7, including only the part of the test where force is increasing. The deviation is small between different measurements before damage, i. e. the same measurement situation (material, package geometry, measurement position, etc.) gives the same result. The repeatability of the measurements is hence good. We also see a clear separation between the two load cases in most of the signals, indicating that it could be possible to pick up considerably smaller differences than demonstrated here.

Table 2 shows the average electrode values and the standard deviation. It is noticeable that the order of magnitude of the electrode values differs. Looking at the variability for each electrode, the coefficient of variation (standard deviation divided by average value) is below 10 % for most of the electrodes. The few electrodes that have a higher coefficient of variation have a low average absolute electrode value (below electrode absolute value 30 bits), i. e. it is not the highest standard deviation that gives the highest coefficient of variation. Where the coefficient of variation is high the change of indentation is small. To compare the order of magnitude of these coefficients of variation, note that the tolerances of properties of industrially pro-

duced cartonboard are often wider than 10 %. For example, the specification of the cartonboard studied here (see Table 1) tolerates bending resistance 15 % below nominal value. Biotac has a pressure sensor that measures the total static pressure P_{DC} in the fluid inside the sensor. We know from previous work that the total static pressure measured in the sensor at a given force is related to the compliance of the surface the sensor is pressing down on. Specifically, a more compliant surface gives a higher static pressure at the same force (Su et al. 2012, Eriksson et al. 2020). There is a small but significant difference between the pressures measured in this case, an effect of being closer to the corner in position B than in position A, with the tuck-in flap providing extra stiffness.

The value measured by each electrode in the sensor is influenced by the local properties of the package, i. e. of how the package encloses the finger-like sensor. A positive electrode value means that more fluid is at the electrode position compared to initially (swelling of the finger), while a negative electrode value corresponds to less fluid at the electrode position than initially (indentation of the finger).

There is an interesting pattern in the electrode readings, where position B (red, Figure 7) has lower electrode values for electrodes 7–10 than case A (blue, Figure 7) on the flat area on the tip of the BioTac at the same force. For the central backward electrodes 17–19, the trend for A and

Figure 7: Measurement results for load case A (blue) and B (red). The solid lines show the average values and the shaded region shows are four standard deviations wide ($\pm 2\sigma$).

Figure 8: FEA results for z displacement in position B.

Figure 9: Displacement of the cartonboard at 6.6 mm indenter movement, calculated at different positions along a path running in the y direction and passing right under the indenter (zero on the y axis).

B is reversed. An explanation to the lower 17–19 electrode values in A can be that where the panel is less stiff (position A), more of the BioTac contact is shifted backwards, towards the MD-crease, causing lower electrode values of the back electrodes for position A.

In Figure 8 the FEM simulated indentation in position B is shown. In position B, the distance to deformation start of the panel is shorter towards the insert tab than towards the other side. Hence the angle up towards the undeformed panel is steeper on the insert tab side than on the other side. A high angle up to the undisturbed surface, generally gives lower electrode results, than a low angle. This difference is also present in the position A and stems from the design of the package, rather than the load case.

In Figure 9, we see that the difference between the two load cases is small in the area around the indenter. While there are differences in the displacement far away from it, the BioTac readings should only be influenced of the behavior within approximately 10 mm of the center point.

Given that clear differences between the load cases are seen in the data from the BioTac, but not in the data from the uniaxial tester, nor in the FE analysis with a rigid indenter, it seems as though the BioTac interacts with the package in a way that is different to the rigid indenter. It

picks up subtle differences in this interaction, that could be similar to the differences that a human test person could perceive. This also points to the complexity of designing a test method for packages of arbitrary designs, even if limited to parallelepiped shapes. It would perhaps be wise to test not only in a single position. The presented method would be suitable for such an approach, as these results demonstrate that meaningful differences can be picked up at low force, with presumably mostly reversible deformation.

More work will be necessary to draw further conclusions about how the BioTac interacts with the packaging material and structural features and to how it maps to human tactile perception. This method opens possibilities for further studies linking physical parameters of the gripped object to the mechanical interaction and coupling them to grip sensation.

Conclusion

We present an objective, repeatable and easy to use laboratory measurement method for measuring the mechanical interaction between an artificial finger-like sensor and a package.

Evaluation of the method shows good repeatability, the variability in the measurement result is within a few percent in most cases. The sensor signal gives information on deformation of a finger-like object when it interacts with a package. When the position of the sensor is changed, the accuracy is similar and the change in most signals is far greater than the variance of the signal, indicating good signal to noise ratio. The method could be adapted to measuring package properties in industry as it is both fast and reliable. The advantage of the presented method is that it is an objective, well-defined and easy to use method to measure influence of package properties at a studied load case with finger-like sensor package contact.

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