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The theoretical optimization of the arrangement of sandwich filling components

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A B S T R A C T

The study aims to endorse the relevance of tribology in daily life and to promote tribology to a broader demographic. Sandwich filling slumping in its packaging, known as a skillet, is termed "drop". The authors found that the optimal arrangement of sandwich fillings to prevent drop had not been researched. The Bacon Lettuce and Tomato (BLT) and the Chicken Salad sandwich were investigated. An optimal arrangement for each sandwich that minimised drop is suggested. The coefficient of friction of each interface was determined experimentally and a theoretical optimal arrangement was suggested and validated using a numerical model. An improvement of 9.9% was observed between the optimally and worst arranged Chicken Salad sandwich models. For the BLT the improvement was 8.2%.

1. Introduction

The invention of the chilled packaged sandwich took place in the spring of 1980 when Marks and Spencer began selling packaged sandwiches for as little as 43 pence [1]. In the UK, the chilled packaged sandwich industry is now worth approximately £8 billion per year [1] and at The University of Sheffield more than 100,000 sandwiches, in skillet packaging, are sold across campus per year. It was decided that the data supplied by the university was representative of the sandwich market in the UK and was used as the benchmark for this study.

After conducting a literature review it became apparent that no published scientific work had been conducted to investigate the drop. However, some interesting ideas of ways to reduce the probability of sandwich fillings falling out of a sandwich during eating were suggested in a book by Dan Pashman titled Eat More Better [2]. For instance, it is suggested that placing greens such as lettuce between layers, can result in the sandwich becoming less prone to falling apart. It is also advised that placing sliced tomatoes, cucumbers and avocados next to each other is undesirable. Another suggestion within the book states that there is a relationship between the stiffness of bread and the slipperiness and stiffness of fillings within a sandwich, i.e. softer bread reduces the probability of drop. These ideas recur throughout this study and are tested in an effort to reduce drop. The data provided by The University of Sheffield suggested that the five most popular sandwich fillings are all components of the Chicken Salad and BLT varieties of sandwich. As a result, these two sandwiches were chosen as the subjects of the research for this study.

The primary objective of this study was to identify, experimentally, the frictional and tribological properties of each ingredient used in the fillings of Chicken Salad and BLT sandwiches. The next objective was to analyse the results of these experiments and develop a model that theorized the optimal arrangement of fillings within each sandwich. An experiment was conducted with a whole sandwich to observe the drop of two different arrangements of Chicken Salad

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sandwich and validate the theoretical model. A Finite Element Analysis model was also generated using ANSYS® in order to numerically model the scenario of a sandwich standing upright in skillet packaging and thus the drop.

2. Mechanical Properties of Sandwich Components

"Texture" seems to be used as a blanket term in literature, most notably in journals related to food technology, and encompasses some of the most important mechanical properties of food. In the food industry, measuring texture parameters such as stiffness and hardness is vital for quality control and improving salability. The mechanical properties of each sandwich filling ingredient used in the Chicken Salad and BLT sandwiches, that were required for the production of the finite element model in section 3.2, are presented in Table 1.

Table 1 - Mechanical properties and dimension of the fillings from measurements of the experimental samples and various sources or calculated.

Filling	Diameter (mm)		Length (mm)		Width (mm)		Thickness (mm)		Density (kg/m^3)	Poisson's ratio	Young's modulus (Pa)
	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation			
Cucumber	35	0.8	-----	-----	-----	-----	3.7	0.3	440 [3]	0.2	1.3×10^7 [4]
Lettuce	-----	-----	50	4.5	46	1.2	1.0	0.2	417	0.2	4.5×10^5 [5]
Tomato	48	2.5	-----	-----	-----	-----	5.7	1.2	1120 [6]	0.2	1.8×10^4 [7]
Bacon	-----	-----	60	2.5	21	6.4	1.3	0.1	524 [8]	0.2	1.0×10^4 [8]
Chicken	-----	-----	44	1.0	37	2.5	7.0	1	600 [9]	0.2	1.4×10^5 [10]
Bread	-----	-----	130	0	110	0	15	0	93 [11]	0.2	3.5×10^4 [11]
Mayo	-----	-----	130	0	110	0	1.0	0	1014 [12]	0.2	1.0×10^3 [13]

Bread provides the main structure of every sandwich, so understanding and determining its mechanical and chemical properties is vital when trying to determine how to prevent drop. It was found that the adherability of bread to the filling is affected by temperature [14]. Starch retrogradation (staling) occurs when the amylose and amylopectin chains within gelatinised starch realign themselves as cooked starch cools [15]. As bread cools below the gelatinisation temperature of starch (150°C) the molecules of amylose and amylopectin rearrange themselves to form a more crystalline structure. The water that was absorbed during baking is slowly expelled and evaporates causing bread to become progressively harder and dry [15]. Freezing prevents bread from staling, but staling occurs rapidly if bread is stored in the refrigerator. The rate of retrogradation is highest at 50°C and results in increased adherability between the bread and the filling [15].

Major changes in the texture of fruits such as tomatoes and cucumbers occur during ripening. Literature appears to suggest that two of the most important textural parameters are "firmness" and "mealiness". The firmness of a fruit is dependent on the size and shape of cells in the exocarp, or skin of the fruit and the strength of the cell walls within the mesocarp, or fleshy part of the fruit [7]. Small cells in the skin and stronger cell walls result in a firmer overall texture [7]. Mealiness is the parameter that quantifies the granular, powdery texture of the fruit that occurs because the cells are more elongated and grouped together in bundles and the cell walls are strong but the connections between them are weak [7]. In cold environments (such as in a refrigerator) the cell walls begin to break down and result in a mealy texture unless the fruit is perfectly ripe before it enters the refrigerator [7]. It was speculated throughout this study that the textural properties (i.e. the mealiness) of the fruits may have influenced the measured coefficients of friction.

Meat perceptibility is dependent on the interaction between sensory and physical processes during chewing. Tenderness has been described as the most important sensory characteristic of meat particularly when it comes to boneless, skinless broiler breast fillets [10]. Meat texture is dictated by the presence of factors such as the amount of intramuscular fat and the water holding capacity. However, it is the quality of collagen which dictates the toughness of the meat [10].

Conventional mayonnaise is a mixture of oil, vinegar, egg, sweetener, salt, thickener, stabiliser and flavourings. All these constituents are carefully blended to form an oil droplet foam network which is stabilised by an emulsifier such as egg yolk [16]. High fat mayonnaise is more susceptible to spoilage due to factors such as oxidation, yeast and moulds. As a result, the sandwich industry usually employs a reduced fat alternative containing less oil and/or egg yolk.

The size of oil droplets present within the continuous water phase of mayonnaise, ranges between 0.1 and 10μm [17]. The oil content in mayonnaise is usually approximately 70 to 80%, where a higher oil content yields a firmer structure [18]. It can therefore be assumed that reduced fat mayonnaise is less viscous than its full fat counterpart.

At the interface between oil and water there is a thin film where emulsifiers are situated. At this region the continuous water phase surrounds the oil droplets and contains the flavouring substances of mayonnaise [19]. Granules of egg yolk adhere to each other and to apoproteins situated at the oil-water interface forming a network. Oil droplets within the network are in a glass state with Van der Waals attraction between them. The emulsion becomes more stable and the viscosity of the product is increased if there are stronger, more numerous Van der Waals interactions between the droplets the emulsion [20].

In the production of packaged sandwiches mayonnaise is mechanically deposited. It must be sufficiently viscous not to slide out of the two layers of bread, but not too viscous that it will not slide down and exit the hopper. It has been reported that the viscosity of mayonnaise ranges from 5 to 10 Pa.s depending on temperature [21]. Along with improving the flavour of the sandwich mayonnaise is also used as an adhesive [22].

3. Methods and Experiments

The coefficient of friction of each of the sandwich component interfaces for the Chicken Salad and BLT were identified experimentally using a sliding friction rig shown in Figure 1. The static coefficient of friction was then measured assuming four basic empirical laws of friction [23]:

- There is a proportional relationship between the maximum tangential force before sliding and the normal force when a static body is subjected to an increasing tangential load.
- The tangential friction force is proportional to the normal force in sliding.
- Friction force is independent of the apparent contact area.

Using these assumptions, the coefficient of friction, μ, at the interface of two materials in contact can be described by the following equation:

$$F = \mu R \qquad \text{Equation (1)}$$

where R is the reaction (normal) force at the contact and F is the friction force that resists motion in the direction parallel to the contact interface. The coefficient of friction, μ, for different interfaces can be obtained using this relationship and a tilting platform (Figure 1).

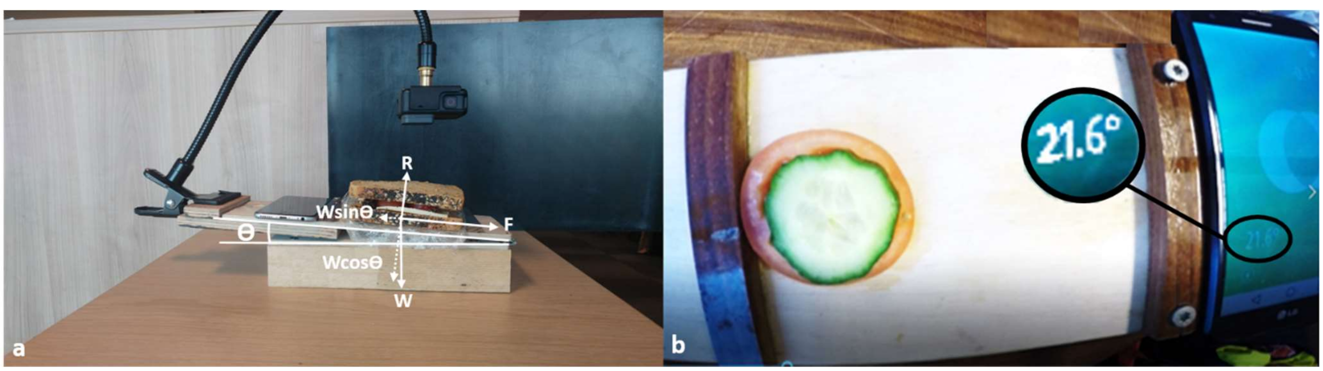


Figure 1 - (a) Tilting rig; (b) view from mounted camera showing cucumber tomato interface under test with angle (21.6°) displayed on mobile device.

The sandwich components were placed on the top surface of the rig, along with a device that displayed the angle, Θ of the surface. A camera mounted overhead recorded the motion of the sandwich components and the angle displayed on the device, whilst the rig was tilted gradually by hand at a rate of approximately 5°/sec. Resolving the forces in Figure 1, in the directions of R and F, results in the following equation for μ:

$$\mu = tan\theta \qquad \text{Equation (2)}$$

The motion of the components in the recordings was observed and the value of Θ at which the top component began to slide was recorded and used to calculate μ. For most components the onset of sliding was evident, but it was noticed that lettuce appeared to slide at an extremely slow rate until it eventually reached a critical point where it fell completely towards the ground. For every experiment, the moment that any sliding was detected was taken to be the point at which the coefficient of friction was calculated. Each recording was played back frame by frame, around the critical point to obtain the exact moment that sliding had commenced. As a result, the precision to which μ was calculated was limited by the frame rate of the recording, 100 Hz, the precision of Θ, +/-0.05°, and to some extent the resolution of the recording, 1280 x 720 pixels.

The food components used in the experiment were sourced from a local convenience store and were cut to the typical size of the fillings found in packaged sandwiches. Specific dimensions of the food pieces used in the experiment are shown in Table 1, along with their associated mechanical properties that were obtained experimentally and from literature. Three samples of each ingredient were used when compared to the size of the pieces in a skillet packaged sandwich. Therefore, the mean average measured dimensions among the three different samples of each filling were recorded. The density of the lettuce was estimated by averaging the weight of each of the cut pieces and dividing by the volume, based on a rectangular shape using the measured dimensions.

3.1. Theoretical model

A simple theoretical model of the forces acting upon the sandwich fillings was developed using Equation (1). The model was used as a tool to predict the optimal and worst order in which to arrange sandwich components to prevent drop.

The sandwiches that were considered in this study are layered, with four separate components and mayonnaise spread on both slices of bread. Each layer in the model (Figure 2) represents a different component of the sandwich. Layers 1 and 4 are assumed to be stuck to the bread with mayonnaise and layers 2 and 3 are free to slide depending on the friction force and weight of each component. The bread is not shown in the model because the primary focus of this study is the optimal order for the arrangement of fillings which is independent of the bread. The model makes the same assumptions listed for Equation (1) and the following further assumptions:

- The normal force (*N*) at each interface does not change with time and is the same for all the fillings.
- Static coefficient of friction is used to determine the onset of sliding; the dynamic coefficient of friction is not considered but is assumed to be less than the static coefficient.
- Mayonnaise acts as an adhesive layer and does not slide.

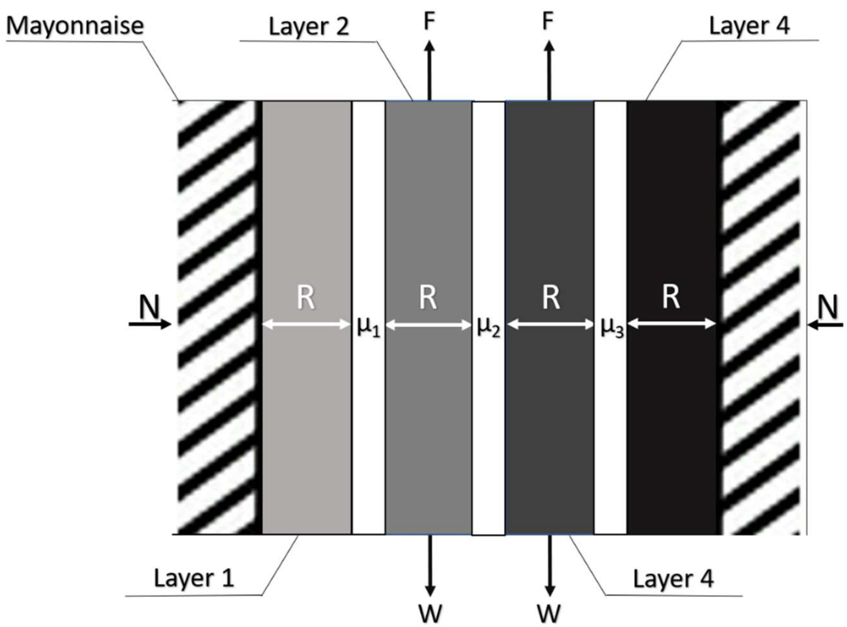


Figure 2 – Layered sandwich theoretical model

Due to the distinctive nature of the system and the challenges encountered when attempting to experimentally determine frictional forces, the system was simplified so that it was assumed that the layers of a sandwich comply with Coulomb's law of static friction. Coulomb's law of friction, otherwise known as Amontons' third law, states that for two dry surfaces sliding against each other, the magnitude of the dynamic friction exerted by the surface is independent of the magnitude of the velocity of the sliding of the surfaces against one another [24]. Coulomb referred to the force required to set in motion a body that lay in a state of rest on an even surface as the force of static friction. He deduced that this force was approximately proportional to the normal force applied to the body [24].

3.2. Numerical model

The geometries of each component of the two sandwiches are shown in Figure 3 below as well as the contact relationship required for modelling. To simplify the modelling and analysis, the geometries of the fillings were assumed to be regular and uniform and the Poisson's ratio of all the components was deemed to be equal. A value of 0.2 was used for the Poisson's ratio. This was an approximation based on results found in literature that identified the Poisson's ratio for apples was 0.17 [25] and between 0.2 and 0.26 for cooked meat [26].

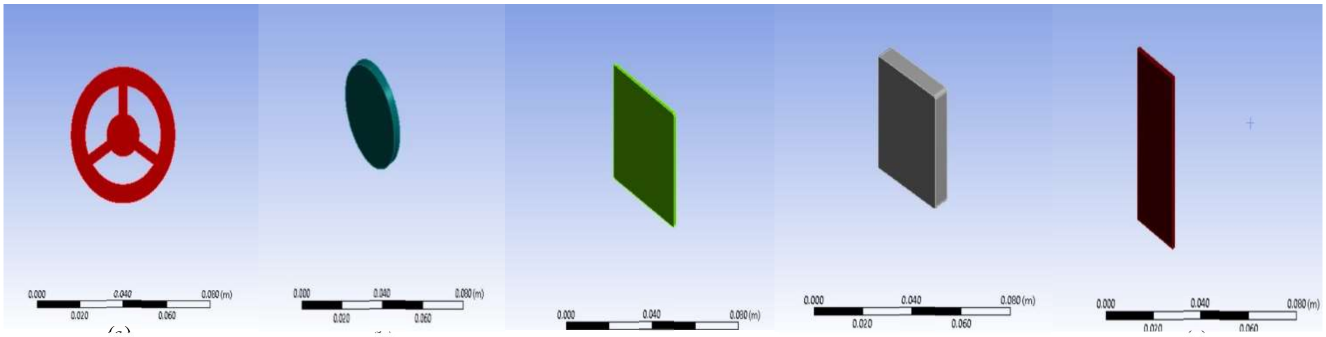


Figure 3 - Geometry of the fillings: (a) tomato (b) cucumber (c) lettuce (d) chicken (e) bacon

The optimal and worst arrangements were modelled according to the order derived from the theoretical model (that is specified in Table 2) and are presented in Figure 5. The contact conditions of the fillings were defined according to the coefficients of friction provided from the experiments (Figure 6). Contact sizing was employed for meshing and the Newton-Raphson method, zero stiffness and mass coefficient were all defined in the software. The assumptions made in the theoretical model (Figure 2) concerning Coulomb's law were replicated in the numerical model. The fillings were subjected to gravity and the bread was modelled as a fixed support, fixed at the bottom surface. A normal force was applied to the bread as it is in the theoretical model Figure 2. Some of the filling components, such as tomato and mayonnaise were assumed to be bonded to some degree due to the high measured friction coefficients. Displacement probes were defined on the fillings to measure the relative displacement in the vertical direction and the displacement of each component was recorded. The model was produced using transient force conditions to allow multiple models to be resolved in a short time period. This time period is shown in Figures 7-10 and was considered convenient to allow the different arrangements to be compared. Mesh convergence of 0.5% was found at a 7mm mesh size. This same mesh was applied to all models.

3.3. Whole sandwich experiment

Sandwiches were constructed and clamped in position to allow for the components to drop without obstruction as shown in Figure 4a. The vice was adjusted to allow the sandwich to be clamped in position without compromising the appearance of the sandwich and crushing the bread and other components, so that it was representative of how a packaged sandwich would appear on shop shelves. The whole assembly was left in position and a camera recorded a

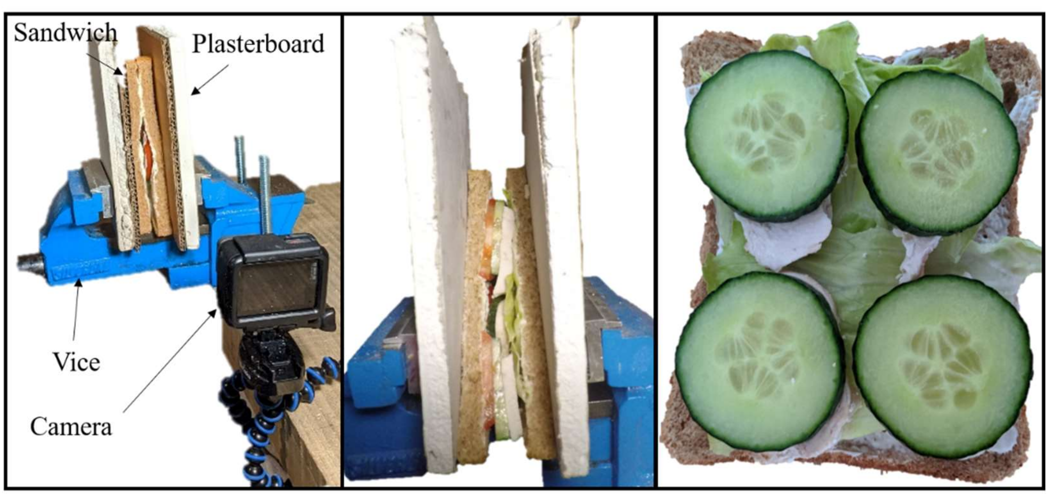


Figure 4 - (a) Experimental set up for replicating sandwich drop. (b) Sandwich clamped in position at start of experiment. (c) Sandwich part way though construction.

photo every 60 seconds for up to 9 hours. The catalogue of photos was stitched together into a time-lapse video so that the drop of the components could be observed and played back resulting in approximately 10 seconds of footage for each experiment.

The sandwiches were constructed so that layers did not overlap as can be seen in Figure 4c. This was to replicate the construction of the theoretical and numerical models and also to make component interfaces easily distinguishable when viewing the footage from the experiment. A whole sandwich was constructed using ingredients that were processed in the same way as the ingredients in packaged sandwiches. For example, low fat mayonnaise was used along with processed chicken and bacon pieces that were supplied pre-cut, to ensure that the ingredients were as close as possible to the varieties found in packaged mass-produced sandwiches. 9.5mm thick plasterboard pieces were used to spread the load applied from the vice because they were easy to cut and readily available. Furthermore, the bread was supported at the bottom by the vice, and a bread border was kept to allow the sandwich fillings to be free to fall towards the bottom of the vice. This border is shown by the gap between the edge of the fillings and the edge of the bread on Figure 4b.

4. Results and Discussion

4.1. Frictional properties of different fillings

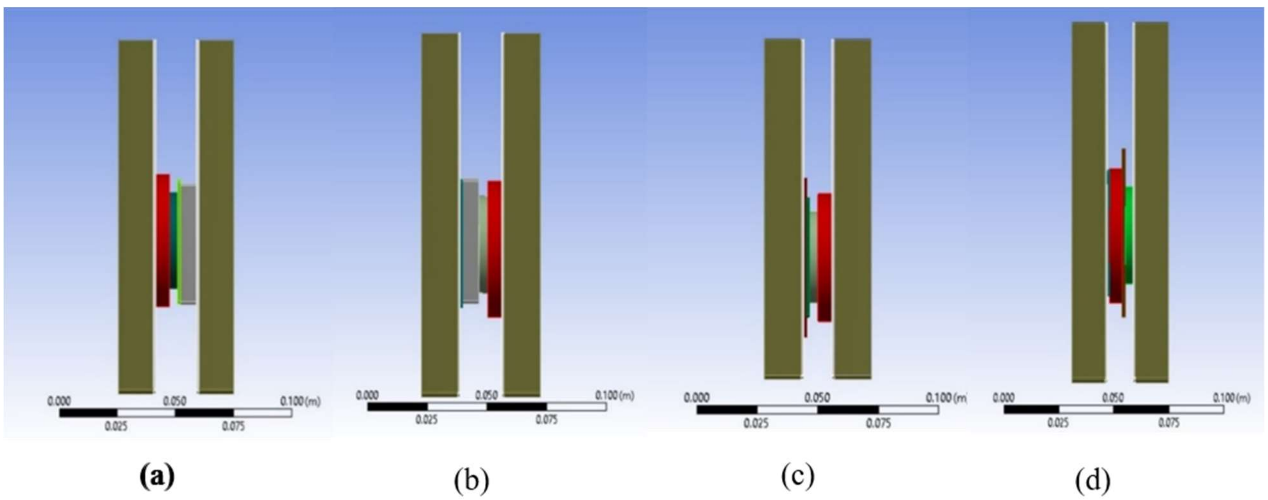


Figure 5 - Chicken Salad and BLT arrangements: (a) Optimal Chicken Salad, (b) Worst Chicken Salad, (c) Optimal BLT, (d) Worst BLT

The friction coefficient for each of the component interfaces found in BLT and Chicken Salad sandwiches was obtained using the tilting rig. Each interface is the mean average of three repeats using fresh components each time. The error bars in Figure 6 represent the variance of the results and therefore indicate the reliability of the data.

The coefficient of friction for each of the components against bread was also identified. However, when mayonnaise was introduced between the two, any sliding between bread and another component was eliminated. Based on the information collected in the literature review, two applications of reduced fat mayonnaise were tested. Firstly, 9g was spread evenly over a slice of bread and then 18g was spread evenly over a new slice. It was found in both cases that mayonnaise behaved as an adhesive, where no sliding occurred for any component that was in contact with mayonnaise. This result corroborated the theories suggested in literature. Therefore, the friction coefficient of any mayonnaise interface using the tilting rig could not be measured.

The tomato-cucumber interface showed a significantly higher friction coefficient than any other interface. The height of the tomato-cucumber bar in Figure 6 is limited to 5 but in the experiment, sliding occurred at an almost vertical 90° angle, resulting in a calculated coefficient of friction of 46. This contradicts the hypothesis proposed by Pashman, [2] that states placing cucumber and tomato together "virtually guarantees slippage, slideage and worse". In this study, it was hypothesised that the moisture present on the surface of both tomato and cucumber helps to bond the two components together. This contradiction also highlights that the context in which friction is considered is vital. The context given in [2] refers to the likelihood of certain fillings falling out of a sandwich whilst being eaten where the sandwich and its components are subjected to pressure from holding and biting forces. Contrarily, the only significant force that acts upon the components of sandwiches stored in skillet packaging and in the tilt experiment is gravity. Under compressive forces from biting and holding, the bonding between tomato and cucumber may become insignificant compared to the horizontal component of the compressive forces. Alternatively, the "slippage and slideage" quoted in Pashman [2] may be attributed to the formation of a lubricating film originating from the moisture released by each component during compression.

Whole lettuce leaves are referred to as a “friction provider” by Pashman due to their high surface-area-to-volume ratio [2]. The results of this study appear to conform to Amontons’ first law: that the magnitude of friction force is independent of the size of the contact area between the two surfaces. For this reason, lettuce was deemed to not be beneficial for the interfacial friction between itself and other components such as bacon, cucumber and chicken. It can be observed in Figure 6 that these components possessed some of the lowest friction coefficients against lettuce. This is potentially due to friction being

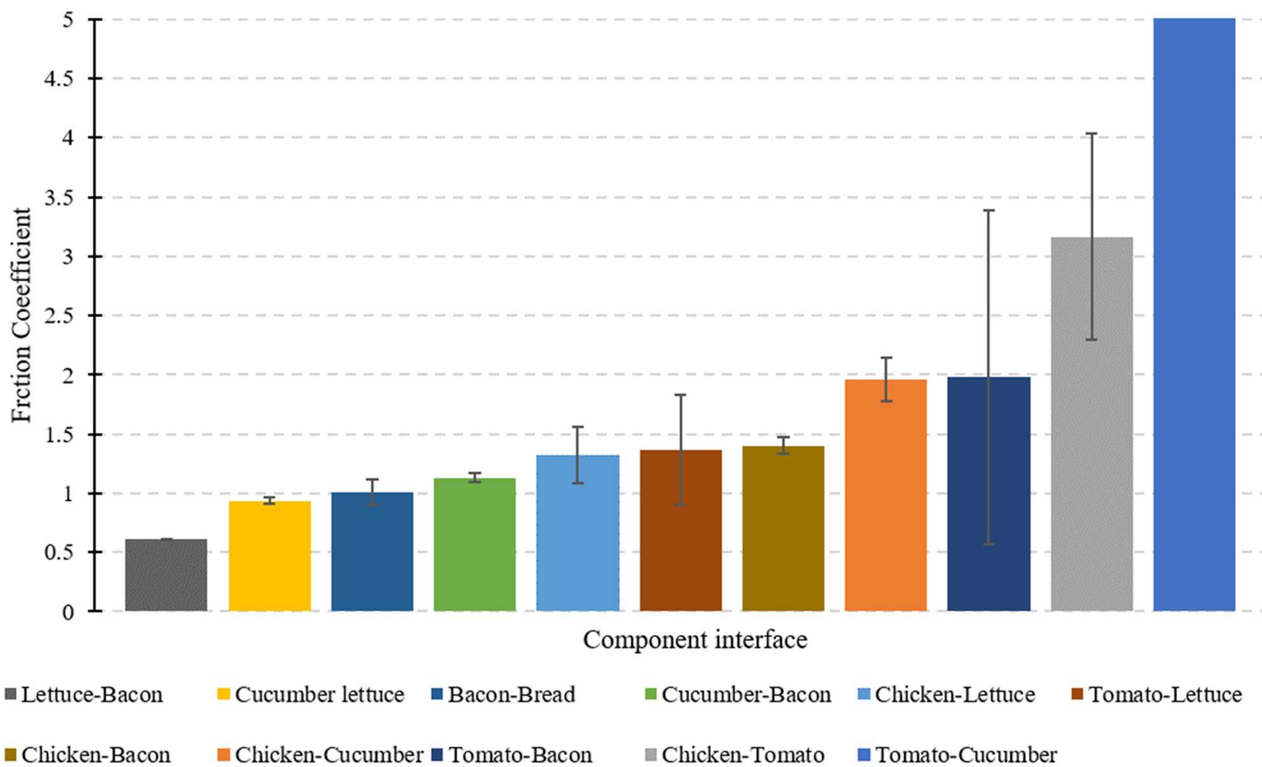


Figure 6 - Average friction coefficient of all the filling to filling interfaces

independent of surface area when the force acting upon the system remains constant (i.e. gravity). Although a larger area of contact between the surfaces of the components would create a larger source of frictional forces, it also reduces the pressure between the surfaces for a given force holding them together. Since pressure is equal to force divided by the area of contact, it can be concluded that the increase in surface area is offset by the reduction in pressure; the resulting frictional forces, then, are only dependent on the frictional coefficients of the components and the force holding them together. If the case described by Pashman [2]) then increasing the surface area would increase the frictional force between the surfaces.

4.2. Optimal arrangement

The optimal arrangement is defined as the arrangement which requires the lowest normal force to prevent drop in the vertical direction. Using Equation 1, and resolving the vertical forces shown in the theoretical model in Figure 2, the value of *N* that would cause drop to occur is represented by the following equation:

$$\frac{W}{\mu} = N$$

Equation (3)

For a sandwich with four layers it follows that there are twenty-four different orders in which to arrange those fillings. Generally, sandwiches do not have a top and a bottom and in terms of the model, the likelihood of drop is independent of whether the components are arranged from left to right or right to left. Therefore, the twenty-four possibilities were reduced to twelve for each sandwich type and the layer/layers that were most likely to drop was dependent on Equation 3. The minimum value of *N* for onset of drop to occur was calculated for each layer to layer boundary, of which there are three as can be seen in Figure 2. The higher the value of *N* (in Figure 2), the more squashed that sandwich would have to be to prevent drop. Using this theoretical value of *N*, the best and the worst ways to arrange each sandwich type is suggested in Table 2. In other words, the lower the value of *N* for a particular arrangement, the less likely it is to drop.

Table 2 - Best and worst ways to arrange Chicken Salad and BLT sandwiches.

Sandwich	Best order	Minimum value of N for onset of drop (N)	First component to drop	Worst order	Minimum value of N for onset of drop (N)	First component to drop
Chicken Salad	1. Chicken 2. Lettuce 3. Cucumber 4. Tomato	0.007	Lettuce	1. Tomato 2. Cucumber 3. Chicken 4. Lettuce	0.060	Chicken
BLT	1. Tomato 2. Cucumber 3. Lettuce 4. Bacon	0.008	Lettuce	1. Cucumber 2. Bacon 3. Tomato 4. Lettuce	0.057	Bacon and Tomato together

During the friction experiments the weight of each of the tested specimens was measured and the heaviest individual components in both sandwiches were chicken and tomato. It is apparent that the best arrangement for each sandwich puts the heaviest components against the mayonnaise adhesive layer and in the worst arrangements the heaviest components are in the centre of the sandwich in Table 2. This follows the same method when eating a sandwich i.e. to have the heaviest ingredients close to the bread as is suggested in [2], but it highlights the importance of the practice in building a sandwich that will be displayed in a skillet to prevent drop, assuming there is an adhesive layer of mayonnaise. In addition to arranging the layers to reduce the normal force required to hold the bread together, the number of components that it is acceptable or not to allow to drop needs to be considered. For example, in the worst arrangement of the BLT it is predicted that both the tomato and bacon will drop together because the friction at the interface formed between them is stronger than the interface formed between each of them and cucumber and lettuce.

4.3. Whole sandwich experiment

The optimal and worst arrangements for the Chicken Salad sandwich were tested for drop using the experimental set-up described in the previous section. It was observed that the worst arrangement displayed a larger amount of drop when compared to the optimal arrangement which somewhat validates the theoretical model and the suggested best arrangements in Table 2. The observed drop occurred in the cucumber and chicken components with a fall of 1-1.5mm over a 3-hour time period. This was estimated by comparing the first image with an image captured 3 hours later as is shown in Figure 7. The measurement scale shown was calibrated using the known dimension of the plasterboard thickness. Using a horizontal line drawn from the lowest point of the cucumber, the position relative to the bottom of the plasterboard was measured.

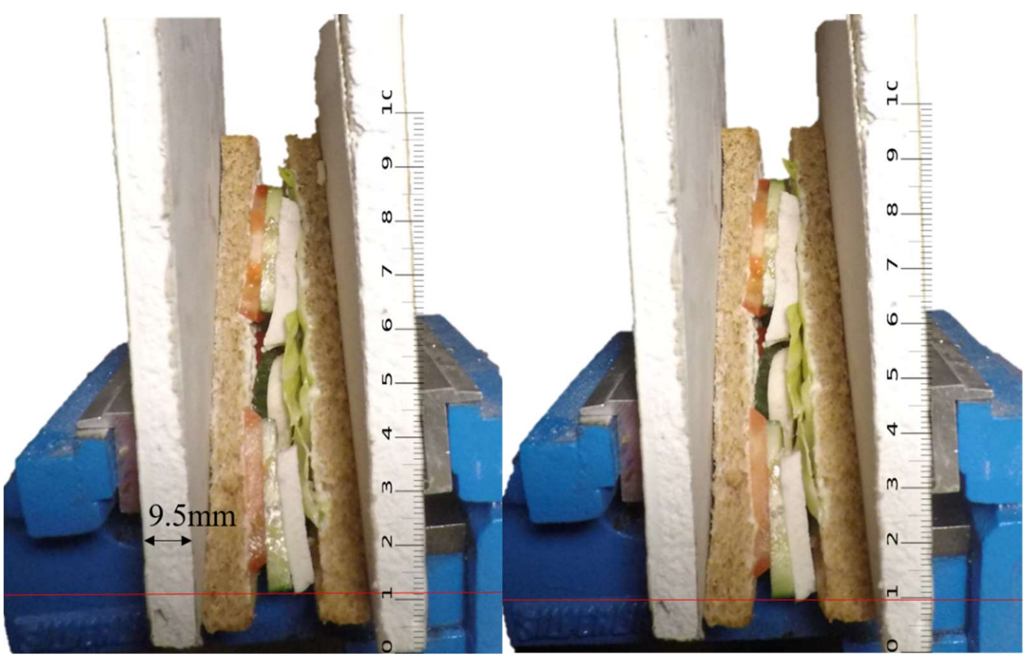


Figure 7 - Chicken salad sandwich arranged in the worst way suggested

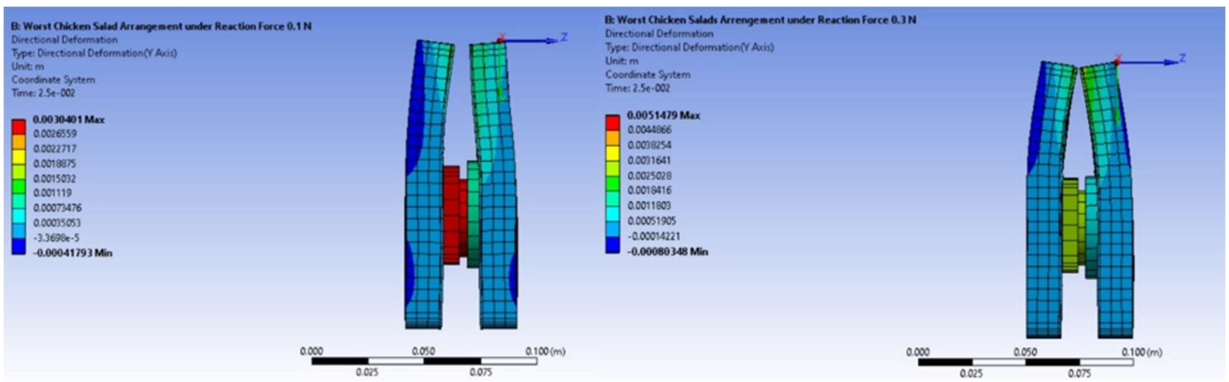
4.4. Model results

The optimal and worst arrangements suggested in Table 2 for each sandwich were numerically modelled using ANSYS®. The displacement calculated in the numerical model of the fillings in the optimal and worst arrangements for each variety of sandwich were compared, and the percentage improvement for the optimal arrangement was calculated.

4.4.1. Effect of Normal Force

In order to investigate the effect of normal force subjected on the sandwiches, three different normal forces of 0.5N, 0.1N and 0.3N were applied. A normal force greater than 0.3N compressed the fillings significantly, deforming them and caused penetration of the bread. Figure 8 shows the worst Chicken Salad arrangement when a normal force of 0.1N and 0.3N was applied.

The maximum drop of the worst Chicken Salad arrangement occurred in chicken and cucumber and was reduced from 3.04mm at a normal force of 0.1N to 2.5mm at a normal force of 0.3N. In other words, an increase in the normal force from 0.1N to 0.3N reduced the drop by 17.8%.

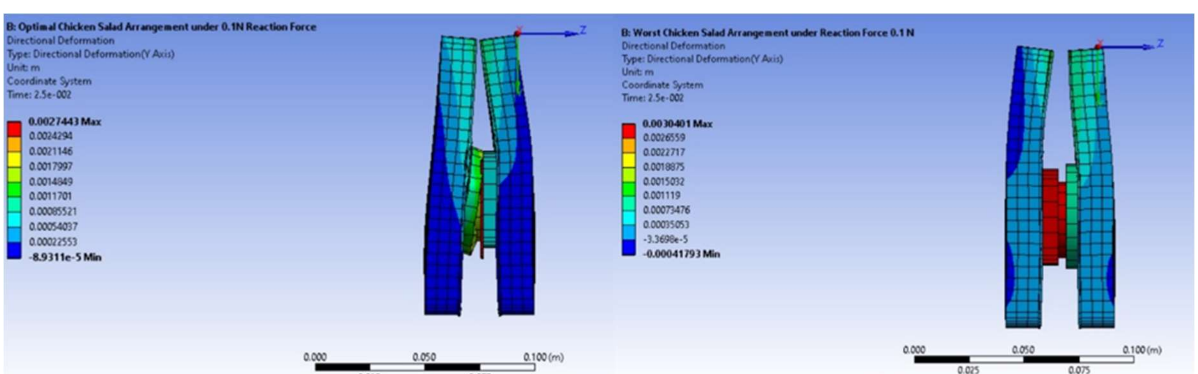


(a) (b)

Figure 8 - Effect of normal force on drop: (a) normal force of 0.1N, (b) normal force of 0.3N.

4.4.2. Case 1: Arrangement of Chicken Salad

The results for the total displacement of the optimal and worst arrangements of the Chicken Salad sandwich are provided in Figure 9. The data collected throughout this study identifies that the minimum displacement occurred in the optimally arranged sandwich and measured 2.74mm. Conversely, the maximum displacement of 3.04mm occurred in the worst arrangement. That is to say, the amount of drop was 9.9% less in the optimal arrangement than in the worst arrangement. The maximum amount of drop, in the optimally arranged Chicken Salad sandwich, occurred in lettuce and the minimum displacement in chicken. Contrarily, the maximum displacement for the worst arrangement occurred in chicken and cucumber and the minimum displacement in lettuce. This agrees with the predictions made using the theoretical model (Table 2).



(a) (b)

Figure 9 - Chicken Salad sandwich: (a) Optimal arrangement, (b) Worst arrangement.

4.4.3. Case 2: Arrangement of BLT

The results of the total displacement of the optimal and worst arrangements of the BLT sandwich are presented in Figure 10. The maximum displacement for the optimal and worst arrangements is 2.79 mm and 3.04 mm respectively and the total amount of drop in the optimal arrangement is 8.2 % less than the drop in the worst arrangement. Figure 10 identified that for the optimal arrangement the maximum drop occurred in lettuce and the minimum drop occurred in bacon. Conversely, the maximum and minimum drop in the worst arrangement occurred in bacon and cucumber. Again, this corroborates the predictions made using the theoretical model (Table 2).

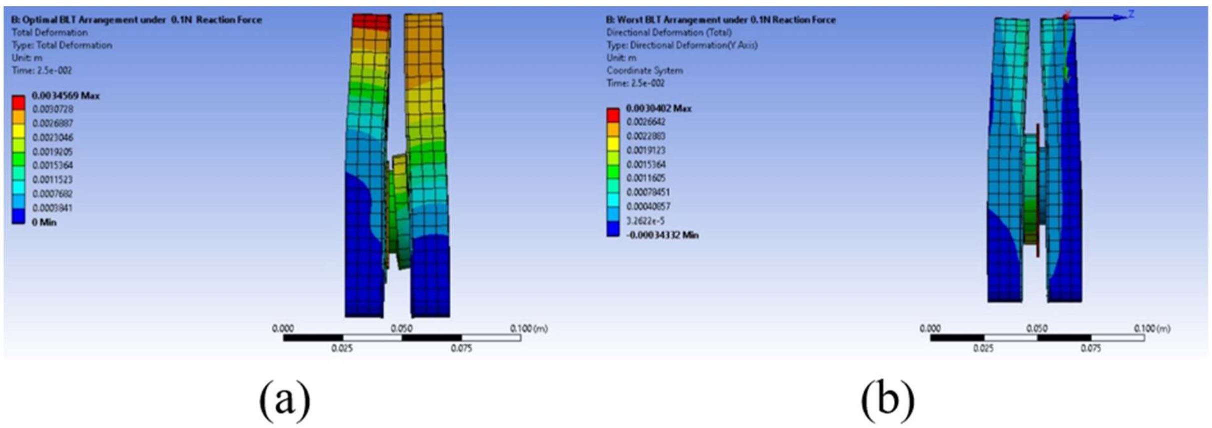


Figure 10 - BLT sandwich: (a) Optimal arrangement, (b) Worst arrangement.

4.4.4. Sensitivity Analysis

In order to study the friction sensitivity of the models, the optimal BLT arrangement subjected to a normal force of 0.1N was considered. The optimal arrangement of a BLT sandwich when all coefficients of friction were reduced by a factor of 10 was compared to the same arrangement when the actual coefficients of friction were applied. The maximum drop occurred in lettuce and was reduced by 7.83% when the actual coefficients of friction were applied.

4.5. Comparison of numerical model to experiment

The numerical model was constructed using a single piece of each ingredient to decrease calculation time. Contrarily in the whole sandwich experiment the sandwich is filled completely. This means that a comparison of the bread deformation between the model and experiment is difficult. To address this, a BLT sandwich in the worst arrangement was constructed in a way as close to the numerical model as possible, as shown in Figure 11.

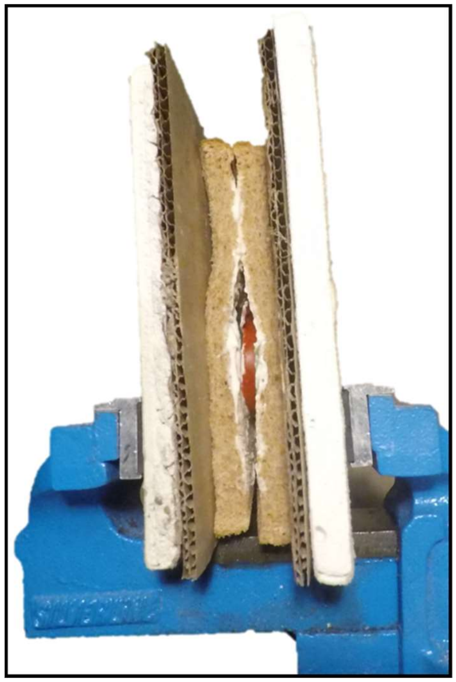


Figure 11 - BLT in worst arrangement with a single piece of each ingredient to replicate numerical model

It is evident that the bread deforms in a similar way to the numerical model and the two pieces meet at the top of the sandwich. Since the normal load is spread evenly on the bread in the numerical model and in the experiment, the load applied in line with the vice clamps, this suggests that the deformation of the bread at the top of the sandwich is primarily down to the force of gravity. This deformation of bread is unattractive to the consumer and highlights the importance of filling a sandwich fully regardless of magnitude of the normal force supplied by the packaging of the sandwich.

4.6. Discussion of the numerical model

The results of the numerical models presented in sections 4.4 and 4.5 validate the predictions made using the theoretical model because the optimal arrangement drops significantly less than the worst arrangement. The BLT appears to be at a slightly lower risk of drop than the Chicken Salad. For instance, the drop of the optimal arrangements of both flavours are very similar at 2.74 and 2.79mm, but the optimal arrangement for the BLT results in 8.2% less drop as appose to 9.9% less drop for the Chicken Salad optimal arrangement over the same time period. The small difference for the between the likelihood of drop for the each flavour could still be significant when it is considered that during transport and handling, such sandwiches will be subject to vibrations which will loosen components and effectively increase the weight force dragging them down, so any gain in stability of the fillings may increase the yield of sandwiches that get put onto shelves for retail. The numerical model adds complexity to the theoretical model by considering material properties such as Young's modulus and Poisson's ratio of each of the components. However, the level of complexity of the real scenario is significantly greater and the following sources of error should be considered if the numerical model were to be developed further:

- Mayonnaise was assumed to be a solid layer when, in reality, mayonnaise acts as a non-Newtonian, pseudoplastic fluid.
- The contact conditions were assumed to be linear but their behaviour in reality is nonlinear.
- The stress and strain of the fillings was assumed to be within the proportional limits in order to derive Young's modulus.
- The roughness and waviness of each component was discounted.
- It was assumed that mayonnaise covered all of the asperities of each slice of bread and there was no direct contact between the bread and fillings.
- The normal force generated by the wall of the packaging was assumed to be uniformly distributed across the surface area of the bread. In reality this would depend on the amount of filling within the sandwich.
- A constant value for the Poisson's ratio was used for all the fillings.

5. Future work

A product of the literature review was the theory that the temperature of a component affects its textural properties and therefore the adherence between each sandwich ingredient. A logical next step for the project would be to conduct the filling friction tests detailed in section 2 and represented in Figure 1, at varying temperatures to investigate the significance of this relationship.

It was also highlighted in section 4.1 that the slipperiness of the fillings such as tomato and lettuce is dependent on the compressive load exerted when a sandwich is being eaten. It would be beneficial to experimentally replicate a sandwich being eaten and measure the interaction between fillings under realistic compressive loads in order to validate the ideas introduced in Eat More Better by Dan Pashman [2].

A complete drop of the sandwich fillings was not observed in either the experiment or through simulations using the numerical model. In reality this would be the case of most concern to the sandwich manufacturer or retailer. The numerical model in this study was limited by the simulation time available to run each scenario. Even at a near zero value of normal force applied to the sandwich the drop observed did not result in a complete fall of the fillings due to the amount of time simulated. Future work on the numerical model should therefore concentrate on increasing the amount of time that is simulated and the processing power available in order to investigate a scenario where complete drop of the fillings occurs. The model could also be applied to investigate the effect of different loading scenarios from situations that might encourage drop, such as vibrations from transportation of the products.

The contact conditions between each filling layer has been idealised to assume uniform complete contact between layers. Further complexity to the shape and properties of each of the fillings in the numerical model should be added in future work. The shape of lettuce and bacon could reflect the waviness of each component in reality as opposed to the flat structure that was modelled in this study.

6. Conclusions

In conclusion the study has found that arranging the fillings so that the heaviest component is in contact with the mayonnaise adhesive layer is an effective way of reducing the likelihood of drop in skillet packaged sandwiches. If a sandwich without a mayonnaise layer is to be considered, the theoretical model proposed can be used to identify the best way to arrange the layers and this has been validated by a numerical model. The role of the greens in this study had the opposite effect to that proposed in literature (namely [2]), where it was suggested that lettuce could be used as a friction provider and that having a tomato-cucumber interface undesirable, but this contradiction highlights that there is a different optimal arrangement depending on whether the goal is to prevent the drop of a sandwich packaged in a skillet or to prevent fillings falling out of the sandwich during eating.

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Competing interest

The authors have no competing interests to declare.

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