USABILITY OF TABS IN SEMI-RIGID PACKAGING

By

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ABSTRACT

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The ability to easily peel the lid of a container is a critical issue for semi-rigid packages used to protect and deliver a myriad of products including medical devices, foods, and beverages. An in-depth search of the scientific literature revealed very little information and several gaps about the fundamentals of peelable semi-rigid packaging opening. Therefore this research had the following objectives: (i) to perform a thorough literature review on packaging usability with special focus on semi-rigid packaging, (ii) to describe the relationship between peel angle and peel force, (iii) to evaluate peel direction during real package opening, and (iv) to evaluate the relationship between tab size and grip choice. A wide range of research methods were used to achieve these objectives including kinetics (the study of forces), kinematics (the study of motions), anthropometrics, computer simulations, package testing, and observational techniques.

First, a theoretical framework for human-package interactions (H-PIM) was created and used to assess the gaps in the research literature relating to packaging usability studies. Second, an affordance-based design method was created and illustrated with a packaging example with tabs.

Third, experimental peel force measurements for two seal geometries were collected varying peel angle every 15° intervals. Experimental data (force vs. angle) for

both conditions followed a U-shaped pattern with minimum values at peel angle 45°. Classical mechanics was then used to derive an equation in which peel force is a function of peel angle. Two approaches were taken to fit the data to this equation: linearization and nonlinear regression.

Fourth, a method was developed to calculate seal strength for a given semi-rigid packaging system and a mathematical algorithm was designed to calculate peel forces. Results show that the proposed mathematical model for peeling semi-rigid packaging can predict experimental values very well.

Fifth, a motion capture system was used to measure peel angles (α) and peel direction angles (β) during an opening task under two experimental setups (i.e., unrestrained and restrained). Mean peel angle measurements fell within the theoretical optimal peel angle range (α=45°±15°). The initial peel direction angle (β_I) measured during the unrestrained opening condition (β_I=48°, *sd*=22°) was very close to the theoretical angle of β=45° confirming that most participants pulled the tab in this direction during the initial stages of the opening task.

Finally, an observational study revealed grip preferences based on tab size. For initial grip of larger tabs, participants tended to use lateral pinch more than pulp pinch or chuck pinch. During pulling, lateral grip was preferred by participants regardless of tab size. Participants' postural preferences were found to be correlated with ways of opening a specific tray design.

This research provides theoretical frameworks, mathematical models, methodologies, and findings that help the design and development of more usable peelable semi-rigid packaging. Many of the conclusions and design guidelines also apply to flexible packaging.

ACKNOWLEDGMENTS

I would like to take this opportunity to officially thank my major professor, Dr. Laura Bix. I have been very lucky of having her as mentor, colleague, and friend. She has been always available to provide her time, insights, and advice. I really wish we can continue collaborating and developing our ideas. We have so much to do yet.

I would also like to recognize my guidance committee members Dr. Gary Burgess, Dr. Tamara Reid Bush, and Dr. Bruce Harte. Their knowledge and skills have been crucial for this research project. Their constant positive attitude is very rare to find. I really hope to continue working and collaborating with them as well when I continue my career in the academia. Dr. Burgess' hands on approach leaves a permanent mark on me. He not only provided his valuable insights but also was constantly proposing ideas and building solutions. Dr. Bush always provided her experience with kinematics testing and generously allowed me to use her testing facility and her research team. Dr. Harte is the reason why I was able to do my master when he was the School's Director. His looking forward thinking is really missed now that he is retiring.

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I would like to express my gratitude to Kraft Foods, in particular to Susan Bodett, for funding my program in the first years. I would like to thank Jesse Blake from Amcor Flexibles for generously providing lids, and Perfecseal for providing the thermoformed trays used in this study.

A very special recognition to all the participants gave their precious time, their contribution was the core of this study.

Another special recognition goes for my business partner and close friend Javier Castillo Cabezas who successfully run our design firm back home during the making of this research.

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LIST OF ABBREVIATIONS

PCD	Product centered design
UCD	User centered design
ASTM	American Society for Testing and Materials
CEN	European Committee for Standardization
ISO	International Organization for Standardization
JIS	Japanese Industrial Standards
DTI	Department of Trade and Industry
LP	Lateral pinch
PP	Pulp pinch
CP	Chuck pinch

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Introduction

A few years ago a large food company approached Dr. Laura Bix, my major professor, to conduct a usability study with flexible and semi-rigid packaging across wide ranging ages of people. Proposed work included testing functionality in the hands of users and ethnography research with a variety of commercial products. After evaluating several products, it was clear that characterizing the physical relationships between the package and the person was critical to uncovering universal truths that could then be employed by designers to enhance the usability of packages. An in depth search of the research literature revealed very little information about the fundamentals of flexible and semi-rigid packaging opening. The fundamental question raised was: what characteristics of a heat sealed package (i.e., seal geometry, peel angle, peel direction, tab size, etc.) have an impact on package openability? This is my quest in this dissertation, an attempt to quantify and describe the optimal features that a tab should have. To reduce variability a specific tray (i.e., a semi-rigid package) was chosen for in depth study. The following chapters narrate experiments and findings:

- **Chapter 2** introduces a theoretical framework for human-package interactions (H-PIM) and assesses gaps in the research literature relating to packaging usability studies. This manuscript is currently under revision for potential incorporation into the special issue on human-packaging interaction at *Packaging Technology and Science*.

- **Chapter 3** introduces an affordance-based design method and illustrates it with a packaging example with tabs. This manuscript is currently under revision for potential incorporation into the special issue on human-packaging interaction at *Packaging Technology and Science*.
- **Chapter 4** explains experiments that characterize the relationship between peel angle and force using a tensile testing machine.
- **Chapter 5** proposes a mathematical model to predict peel force.
- **Chapter 6** describes an experiment using kinematics for measuring peel angles and peel direction angles during package opening with human subjects using two experimental setups.
- **Chapter 7** describes and experiment to evaluate the relationship between tab size and grip choice.
- **Chapter 8** summarizes findings and future research directions.

2

A literature gap-assessment through use of a novel human-package interaction model (H-PIM)

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Abstract

Commonly accepted models from the fields of cognitive psychology and human factors have been adapted and combined into a framework we have termed the human-package interaction model (H-PIM). It consists of an iterative loop comprised of perception, mental processing, and action; the outcome of a design's ability to successfully navigate the loop is dependent on four components: the user, the task at hand, the context of the interaction, and the package itself. This conceptual framework can be used to create and evaluate a wide range of human-package interactions.

Herein, we introduce the H-PIM and use it to outline a comprehensive investigation of the peer-reviewed literature of packaging usability studies. Studies that focused exclusively on child-resistant packaging or labeling were excluded from consideration. As such, a total of 84 publications were included in the reviewed literature. A majority of the reviewed studies focus on motor system issues (with an emphasis on tasks of opening), with few looking at issues of perception or cognition as they relate to package use. Studies employed a wide range of users, and almost a third included people with disabilities. By contrast, the contexts of use studied were very narrow, with very few studies taking place in realistic environments; most occurred in a laboratory setting, or employed methods that did not involve contexts (e.g. computer-based tests and survey methods using pictures of packages). Gaps in the literature are identified and reported.

Key words

Packaging, design, interaction, usability, human factors, model

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2.1. Introduction

Packaging designers have generally taken a product centered approach to design. That is, the technical needs of the product and production issues are central to decision making with regard to the package's design; concerns about the ability to effectively produce, fill, distribute, and protect the contents within are fundamental drivers. Recently, this has begun to change. Packaging developers are beginning to give more consideration to the users' (i.e., consumers') needs, wants, and desires and packaging design decisions are increasingly driven from a more user-centered platform of design (UCD).

Interest in, and application of, a UCD approach for packaging design is likely to grow in the future for varied reasons including: the aging of the population [1], a shrinking base of support available to help aging consumers [2], increasingly hectic lifestyles and changes in the way which we view disability [3-5] (the shift from considering disability as a pathology to a social construct).

The trend to embrace UCD is also reflected in the accelerating development of recognized standards and technical specifications focused on accessible packaging. The International Organization for Standardization (ISO) recently finalized a general framework for guiding accessible packaging design. Using the framework as a guide, WG9, the working group tasked with this, is currently working on a series of standards aimed intended to enhance the accessibility of packaging. Braille for medicinal products, became an international standard in 2013 and the group is currently drafting a methods intended to objectively evaluate ease of opening for consumer products.

UCD implementation in packaging was initially slow because of the tremendous complexities associated with design of experiments that rely on human subjects resulting in the inability to link results between different testing conditions and assessment methods. Common methods for evaluating human-package interactions and package performance include: surveys, interviews, focus groups, ethnography, package testing, timed tasks, etc. However, for these evaluations to be useful, it is crucial a theoretical framework able to relate the inputs and outcomes to one another in a format that feeds design and development. Further, this model must include the complex nuances of the interactions between people and packaging.

A thorough review of the literature reveals that an all-inclusive framework capable of considering, characterizing, and organizing all of the interactions that occur between people and packaging is lacking. As such, the first part of this paper introduces a model which adapts and combines frameworks from other fields into a tool that can be used to organize a UCD approach specific to package design and evaluation. This will enable the multiple nuances of human interactions to be purposefully organized, considered and weighed to evaluate usability and design from a user-centered perspective. The second part of this paper uses this novel model as the basis to assess current packaging literature in order to identify gaps in the research and the most fruitful directions for future work.

2.2. A comprehensive model for human centered interactions

The interaction that occurs between people (i.e., users, consumers) and packaged products is an area in need of study. To provide a framework for creating and evaluating how packaged products perform in the hands of people, commonly accepted models from the fields of cognitive psychology and human factors have been adapted and combined. Namely, the Human Processor Model [6], the Cyclic Interaction Model [7], and the Usability Theory [8].

2.2.1. The human processor model

The Human Processor Model [6] is a simplified representation of the human mind. It postulates that, in order to process information and then act upon it, humans employ three systems:

- The perceptual system: the system which handles sensory stimulus from the outside world (i.e., the five senses).
- The motor system: the system which controls actions (i.e., muscles, bones, organic tissue, etc).
- The cognitive system: the system which supplies the processing to connect the perceptual system (input) and motor system (output) (i.e., the nervous system).

2.2.2. The cyclic interaction model

The second theoretical piece proposes the steps in which product-human interactions take place. According to this model, the interaction between an object (e.g., warning, label, closure, package, etc.) and a person can be described as a cyclic information flow [9] consisting of six stages (see Table 2.1).

Table 2.1 – The six stages of human-package interactions.

Stage	User's System Involved	Description
Exposure	None	User is exposed to necessary information. Information may be in the form of the pack features, labeling, or other components of interest.
Perception	Perceptual	Information is input into one or more of the five senses. Typical senses involved in the use of packaging are touch, vision, and hearing.
Encodation	Cognitive	Perceived information is transformed into an internal representation
Comprehension	Cognitive	User recognizes and assigns meaning to the encoded information. Internal representation may be associated with perceived affordances (cues about the operation of things) stored in the long term memory (e.g., information from other sources, previous experiences, etc.). User thinks about the effects of using package features and compares the effect of the action with her/his goals (intentions). Goals may condition comprehension and vice versa.
Execution	Motor	Thought is translated into actions by activating voluntary muscles.
Action	None	User performs an action to change the state of things. The cycle repeats until the user's goals are accomplished.

2.2.3. Usability theory

According to Usability Theory [8, 10], there are four principal components in a "human-machine" system: user, task, tool, and environment. In our argument the "tool" is represented by the design of the packaged product. Since human-package interactions can be described by means of information flow, it can be inferred that success or failure at each step of the Human Processor Model and the Cyclic Interaction Model (see Table 2.1) is dependent on the four inputs specified by the components of Usability Theory (see Table 2.2).

Table 2.2 – The four components of Usability Theory [8, 10].

Components	Brief Description
The user	The characteristics of the person, including perceptual, cognitive, and physical capabilities, beliefs, fears, habits, previous experience, etc.
The task	The series of actions and goals to be accomplished, such as identifying, following instructions and directions, opening, dosing, reclosing, storing, disposing, etc.
The pack	The object of the interaction; the design of the package and its contents.
The context	The physical and social environment in which the interaction takes place. This includes characteristics like lighting, seating, distractions, temperature, pressures, other people, etc.

2.2.4. Human-package Interaction Model (H-PIM)

Herein, we combine and adapt the aforementioned theoretical frameworks to create a concise model we have termed the Human-Package Interaction Model (H-PIM) which considers the wide-ranging factors that impact the user's interaction with packaging (see

Fig. 2.1). Human-package interactions can be described as iterative loops that consist of perception, mental processing, and action that occur within a particular context when an individual performs a specific task (or series of tasks) with a packaged product. The interaction is a cyclic process in which the user's actions may produce an effect and this effect may then reset the state of things, restart the cycle for the next task. Once the user proceeds through the cyclic process, he/she will have accomplished the task associated with the package interaction.

By using the H-PIM during design phases like briefing, ideation, developing, prototyping, and testing, a user-centered design approach is facilitated. Specifically, the model enables marketers, packaging designers (both structural and graphic), and engineers to organize the various needs, abilities, and desires of *users* with diverse *goals* in varied *contexts* in order to purposefully develop design criteria when developing or evaluating package performance. When this exercise is done in depth, possibilities for package design innovation are revealed. Furthermore, key design strategies are likely to be generated by analyzing and prioritizing such factors. The model supports the use of varied user-centered methodologies such as: observation, ethnography, task analysis, context of use analysis, and product benchmarking. The benefits of using this model are as follows:

- Facilitates the identification of possible users and their characteristics.
- Facilitates the identification of possible contexts of use and their characteristics.
- Facilitates the identification of tasks associated with the packaged product.
- Provides a framework for analyzing user-pack interactions in detail from perception to action to identify design issues.

- For evaluation and testing purposes, it can be used to inform testing conditions and compose user panels. Contextual conditions for testing include: the physical environment, lighting, temperature, noise, and distractions, etc.

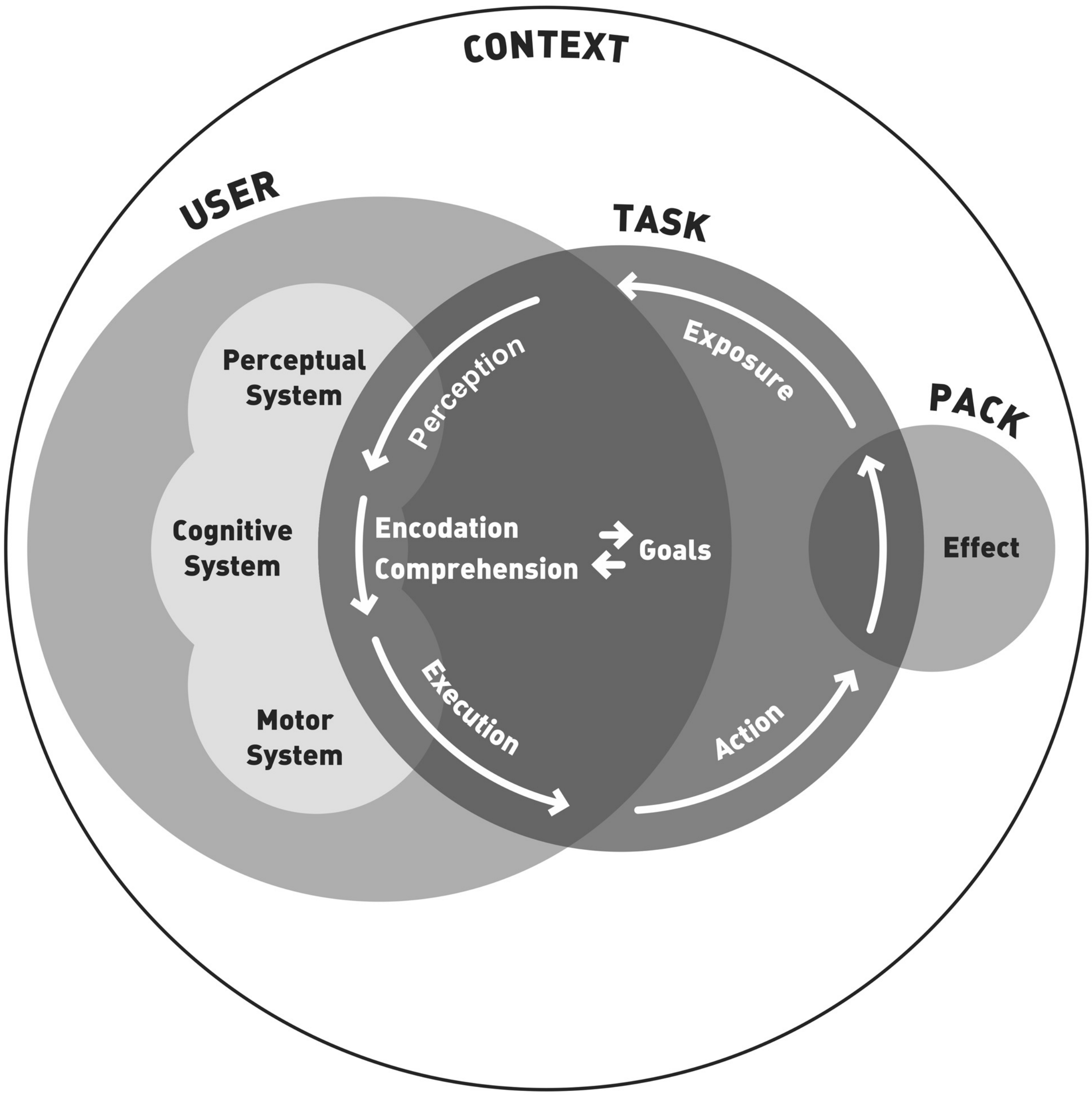

Figure 2.1 - Human-Package Interaction Model (H-PIM).
Based on Card, Monk, and Shackel [6, 8-10].

2.3. Assessment of the literature through use of the H-PIM

In order to identify existing gaps in knowledge and, therefore, the richest areas of future research, the peer-reviewed literature involving human-package interaction were appraised according to four aspects of the H-PIM in order to:

1) To quantify packaging usability studies by *packaging form*.
2) To quantify packaging usability studies by *context of use*.
3) To quantify packaging usability studies by type of *task*.
4) To quantify packaging usability studies by the *users'* systems (perceptual, cognitive, motor) tested.

2.3.1. Methods for literature identification

We conducted an extensive review of the literature focused on human-package interaction using ProQuest, Pira, Web of Science, Google Scholar, the Japanese National Institute of Information's Scholarly and Academic Information Navigator, as well as several journal websites. We limited the search to peer-reviewed publications in English.

Key words in the search included: pack*, container*, jar, tray, bottle, closure, lid, cap, carton, can, flexible, use*, usability, interaction, design, user-friendly, user-centered, human factors, ergonomic*, inclusive, and universal. They were combined in different ways using Boolean expressions. The search was made on title, abstract, and key word levels. The criteria for including a study were that it should address at least one aspect of human-package interactions. It had to have application to a packaging form or use at least one packaging form. It could be experimental or theoretical. Studies conducted exclusively with child-resistant packaging and those studies involving label legibility and processing of its information were not included in the final literature.

The first content check was based on abstract reading. Once relevant articles were identified, they were carefully read and categorized with regard to the four model components. The articles were totaled and distributions reported in the results. This allowed us to identify existing gaps in knowledge regarding packaging use and, therefore, the richest areas of future research.

2.4. Results

A total of 84 publications were identified. Four publications [11-14] described more than one study so the total number of studies for the analysis was 89. They were categorized as below. Percentages have been rounded for simplicity.

2.4.1. Packaging forms

Studies were categorized as focusing on one (or more) of six packaging types (Fig. 2.2):

- Jars (60%, n=53): jars and lug closures.[11, 12, 14-61]
- Bottles (56%, n=50): bottles, jugs, vials, and their closures.[11-18, 20-22, 24-26, 29-32, 35, 36, 40-42, 44, 51, 55, 56, 59, 62-78]
- Flexible and semi-rigid packaging (33%, n=19): blister packaging, yogurt pots, pouches, trays, bags, tear strips, and pulling tabs.[11, 12, 14, 22, 25, 26, 29, 32, 34-36, 42, 51, 55, 59, 67, 79-90]

- Cartons (22%, n=20): folding cartons, boxes, drink cartons.[11, 12, 14, 16, 22, 25, 26, 29, 36, 39, 42, 51, 55, 59, 81, 84, 91, 92]
- Cans (21%, n=19): tins, cans, lifting tabs, and ring pull cans.[11, 12, 14, 25, 26, 29, 31, 34, 36, 42, 51, 55, 56, 59, 69, 93]
- Tubes (6%, n=5): plastics tubes.[11, 26, 29, 31, 35]

The sum of all percentages does not equal 100 because several studies addressed more than one package type.

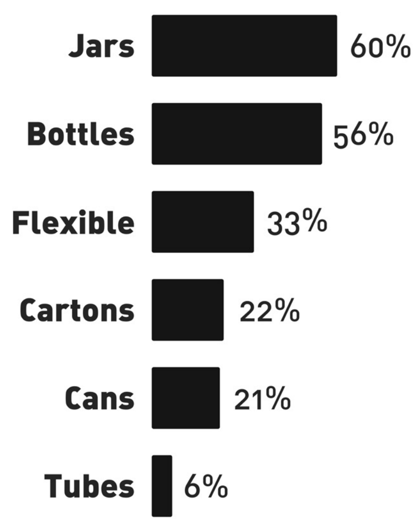

Figure 2.2 – Percentage of studies per packaging form.

2.4.2. Context of use

Context of use is defined as the place in which a human-package interaction takes place. Figure 2.3 shows the variety of contexts of use employed by studies comprising the reviewed literature set. From the total of 89 studies:

- Thirty six percent (n=32) were conducted in lab settings.[11, 13, 14, 16, 19, 23, 27, 28, 30-33, 35, 37, 39, 43-46, 50, 54, 56, 57, 60, 71, 73, 78, 80, 81, 91]
- Ten percent (n=9) took place at participants' homes.[64, 66, 83, 84, 86, 90-92]
- Four percent (n=4) were conducted in retail environments.[12, 61, 83]
- Twenty six percent (n=23) used a context of use but did not provide more details about it.[17, 18, 20, 21, 34, 38, 40, 41, 47, 48, 52, 58, 59, 62, 63, 68, 74-76, 79, 88] It's quite likely that these studies were carried out in lab or university settings which seemed to be the default context.
- Twenty six percent (n=23) did not use a context of use. These studies comprise only-survey studies, which did not test actual packages,[2, 14, 22, 25, 26, 29, 36, 51, 55, 65, 67, 72, 87, 94] testing procedures and apparatus descriptions,[15, 24, 53, 77, 87, 89] and computer simulations and models.[47, 65, 67, 69, 70, 85]

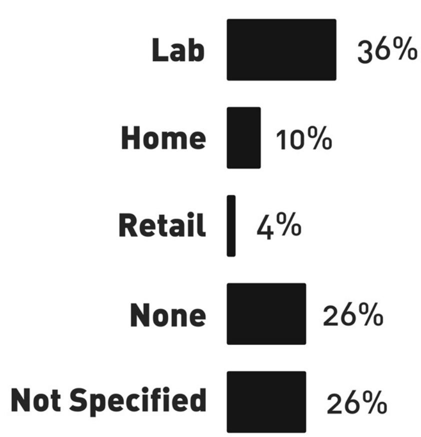

Figure 2.3 – Percentage of studies per context of use.

2.4.3. Tasks

The category "task" is comprised by a series of actions someone takes to achieve a goal. Figure 2.4 depicts the tasks studied within the literature reviewed. Tasks include:

- Information search (11%, n=10).[13, 14, 51, 64, 83, 84, 86, 88, 91]
- Purchasing (12%, n=11).[12-14, 51, 61, 72, 78, 83, 88, 91, 94]
- Carrying or transporting (13%, n=12).[12-14, 25, 51, 64, 66, 83, 88, 91]
- Storing or shelving (12%, n=11).[12, 13, 51, 64, 83, 84, 86, 88]
- Lifting (i.e., unloading, removal from storage) (16%, n=14).[12-14, 24, 25, 32, 51, 64, 66, 83, 88]
- Opening (88%, n=78).[11-25, 27-58, 60, 62-71, 76, 79-93]
- Dispensing (22%, n=20).[11, 13, 14, 29, 51, 59, 64, 66, 73, 74, 77, 84, 86, 88, 90-92]
- Reclosing (18%, n=16).[11, 13, 14, 43, 45, 46, 51, 64, 66, 84, 86, 88, 91, 92]
- Disposing (9%, n=8).[13, 14, 36, 51, 83, 86, 88]
- Did not specified a task (1%, n=1).[26]

The sum of all percentages does not equal 100 because several studies addressed more than one task.

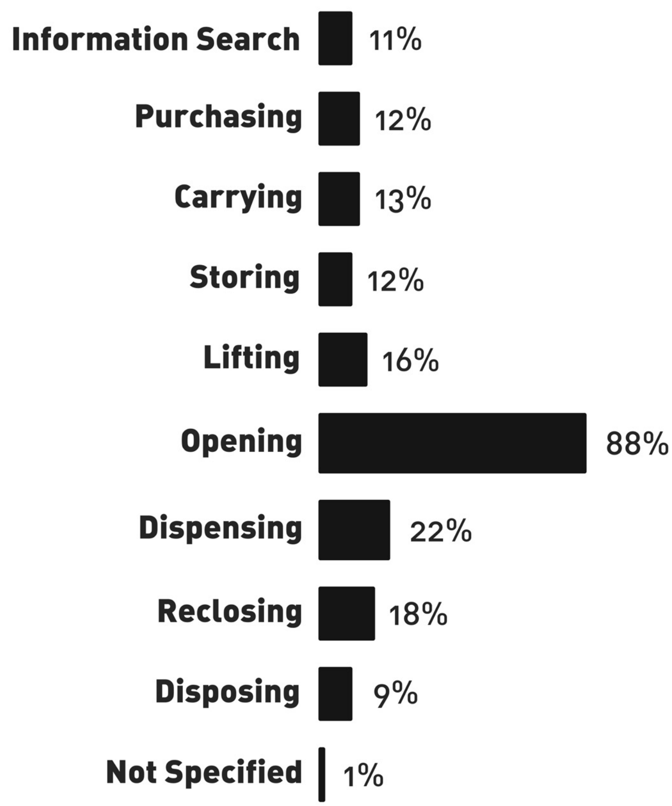

Figure 2.4 – Percentage of studies per tasks with packaging.

2.4.4. Users

To examine how studies dealt with user ability, we enumerated them in two ways. First we characterized the published studies by investigating what portions of the information processing model (i.e., perception, cognition, motor - see Fig. 2.1) were tested during the course of the research. Studies were categorized according to the user's systems involved while using packages (Fig. 5):

- Issues related to the perceptual system were addressed in 35% (n=31) of the studies.[12-14, 22, 25, 26, 29, 34, 36, 51, 55, 61, 64, 66, 71-73, 76, 78, 83, 84, 86, 88, 90-94] Only four studies focused exclusively on perceptual issues.[61, 71, 73, 93]

- Thirty one percent (n=28) of the studies dealt with issues related to the cognitive system.[12-14, 22, 25, 26, 29, 34, 36, 51, 55, 64, 66, 72, 76, 78, 83, 84, 86, 88, 90-92, 94]
- Ninety one percent (n=81) of the studies investigated subjects related to the motor system.[11-28, 30-60, 62-66, 68-70, 74-77, 79-92]

The sum of the three percentages does not equal 100 because several studies addressed more than one user's system.

Figure 2.5 – Percentage of studies per user's systems involved.

Secondly, we quantified all studies by age groups (Fig. 6) and ability. Twenty eight percent (n=25) of the studies included people with some type of disability as participants.[11-13, 16, 25, 27, 29, 32, 46, 51, 59, 64, 78, 81, 83, 84, 86, 88, 92]

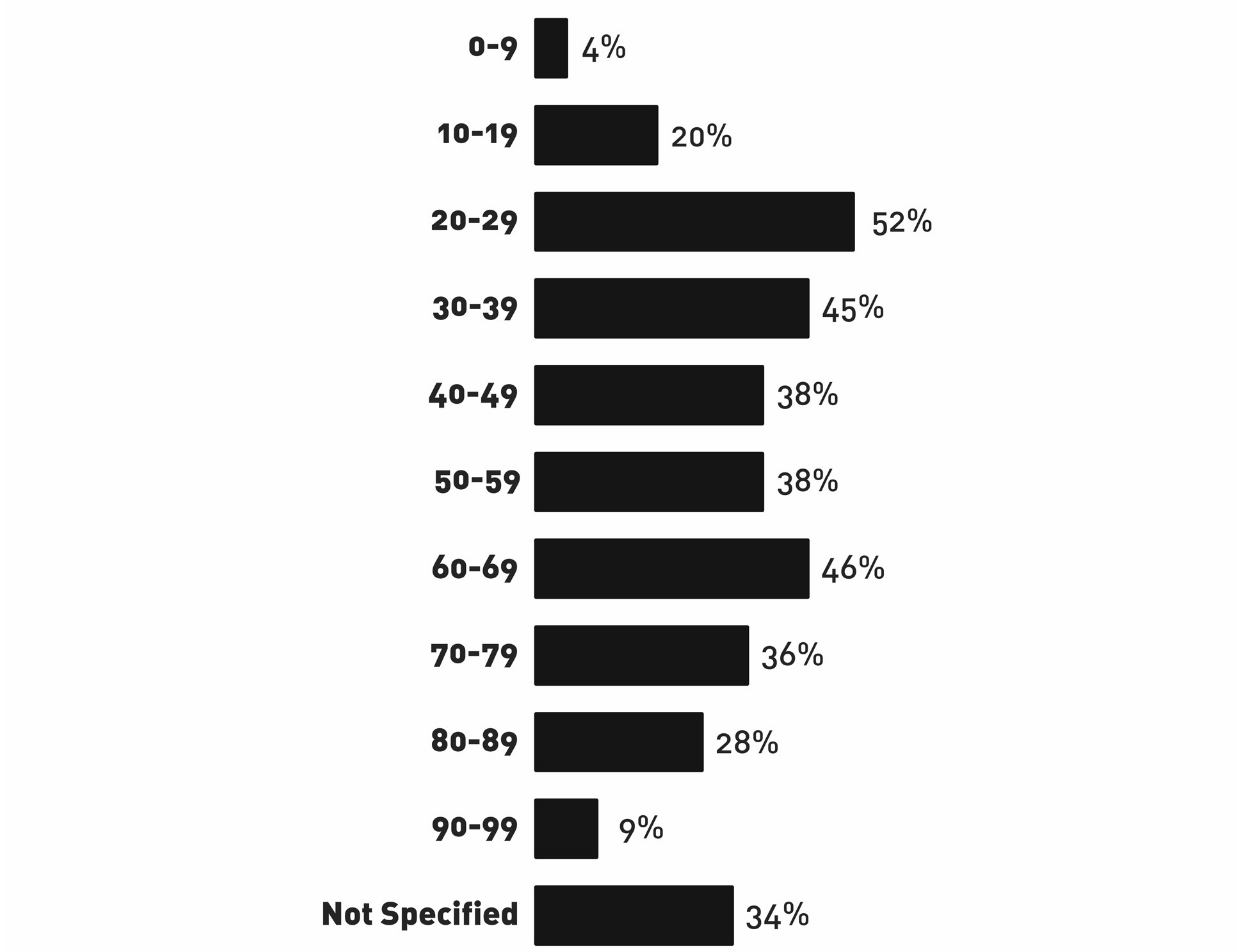

Figure 2.6 – Percentage of studies per age group across all studies.

As a final remark, Appendix A lists all reviewed articles along with information regarding year of publication, first author, sample size, age range, use of people with disabilities, context of use, tasks, user's systems, and packaging forms.

2.5. Conclusions and discussion

We have proposed a unique model to organize and analyze the complexities of human-package interactions. This framework incorporates the four classical components of usability (i.e., user, package, context, and task) and recognizes the involvement of three user's systems: perceptual system, cognitive system, and motor system. The H-PIM model provides a user-centered approach by which intended users, contexts of interaction, and specific tasks can be purposefully considered when designing or evaluating packaging. Herein, we frame our review of the literature regarding human-package interaction against this model. Results are discussed below.

2.5.1. Packaging forms

- Bottles and jars have been the packaging form of choice for the majority of reviewed studies; further, these studies tend to focus on issues related to users' motor system (e.g., strength required to open). More research is needed that focuses on other packaging forms such as flexible and semi-rigid packaging, cartons, cans, tubes, etc.

2.5.2. Context of use

- Roughly a third of the studies (36%, n=32) have been conducted in lab settings.
- Twenty six percent did not report a context of use which poses problems to compare and reproduce results. It's quite likely that these studies were carried out in labs or university settings which seemed to be the default context.

Assuming this, two third of the studies might have been conducted in lab settings.

- A marginal number of studies have conducted on actual homes (10%, n=9) or retail environments (4%, n=4).

2.5.3. Tasks

- The vast majority (88%, n=78) of research concentrates on opening tasks and the physical actions (motor system) required to successfully achieve such tasks.
- The body of research is lacking in information about the distinct tasks that must be accomplished when interacting with packaging.

2.5.4. Users

- The motor aspect of human-package interactions has been heavily explored.
- There is a need for systematic research investigating perception and cognition as it relates to packaging use. For example, only four studies focused exclusively on perceptual issues and focused on cognitive issues.
- It was difficult to categorize studies based on the six steps of the Cyclic Interaction Model (exposure, perception, encodation, comprehension, execution, and action – see Table 2.1). Yet untangling processing is an important aspect of usability. For instance, a closure system may fail, but not because the user was unable to physically open it, but because they did not understand how, or perceive a tab to grasp. As such, there are many opportunities to take a more comprehensive approach to studying packaging usability.

- Age groups between 20 through 89 years old have been more or less evenly included as study participants; in particular young adults ranges (20-39 years old) and older adults groups (60+). The exceptions are three age groups: children (0-9 years old), teenagers (10-19), and people older than 90 years old. A small number of studies included children (4%, n=4) and teenagers (20%, n=18). As the population ages, more information regarding users older than 90 years old (9%, n=8) will be needed.

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3

An affordance-based methodology for package design

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Abstract

The term affordance describes an object's utilitarian function, or actionable possibilities. Product designers have taken great interest in the concept of affordances because of the bridge they provide relating to design, the interpretation of design and, ultimately, functionality in the hands of consumers. These concepts have been widely studied and applied in the field of psychology, but have had limited formal application to packaging design and evaluation. We believe that the concepts related to affordances will reveal novel opportunities for packaging innovation. To catalyze this, presented work had the following objectives: (1) to propose a method by which packaging designers can purposefully consider affordances during the design process and (2) to explain this method in the context of a packaging-related case study.

Key words

Packaging, design, affordance, constraint, usability, human factors.

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3.1. Introduction

From purchasing to disposal, human-package interactions are comprised of several steps that need to be accomplished in order to achieve varied goals. Optimal package designs inspire an immediate understanding of use, opening (where and how), proper and accurate dispensing, reclosure, and disposal. This is particularly important for novel or unfamiliar packaging.[1] Semantic issues, how users understand the meanings of a package, precede ergonomic issues, how users operate it.[2]

de la Fuente and Bix proposed a conceptual model to organize and analyze the complexities of human-package interactions. This model incorporates the four classical components of usability (i.e., user, pack, context, and task) and recognizes the involvement of three user's systems: perceptual, cognitive, and motor. Our review of the literature regarding packaging usability suggests a lack of systematic research investigating perception and cognition as it relates to packaging use.[3] Further, it revealed that research is lacking in many of the distinct tasks performed with packages; the vast majority of research concentrates on opening tasks, particularly emphasizing jars and bottles, and the physical actions (*motor system*) required to successfully achieve such tasks.

Aspects of user's perception and understanding of products have been addressed from a variety of fields such as psychology and product design. In the late seventies, the perceptual psychologist James Gibson revolutionized the field of visual perception by proposing that objects in the environment have functional meaning to an observer.

Gibson invented the word *affordance* to describe any object's utilitarian function, defining affordances as relationships between the "world and actors" (i.e., person or animal). Under Gibson's archetype affordances are all the "action possibilities" latent in the environment independent of an individual's ability to recognize them.[4, 5] Within this frame, the individual design features of an item, such as the pull tab of a can, have the potential to catalyze actions in the user (e.g., can opening). Instead of seeing a can with a pull tab, individuals could see an opportunity to open the can.

Donald Norman, a cognitive psychologist specializing in usability issues, drew on the theory of affordances and applied it to user-product interaction by introducing a narrower concept called *perceived affordances*.[6, 7] Perceived affordances refer to the object characteristics that are perceived by users which convey the ways that the user could interact with the object to accomplish a task. Form, color, weight, and the materials of an object incite possible user actions. These *perceived affordances* provide cues about the operation of things. When designers take advantage of affordances, people can intuit the use of an object without the need for instructions or explanatory labels. Catalyzing appropriate perceived affordances through thoughtful design consideration is, therefore, a major key to usability. From this perspective, if a simple object needs instructions, its design is flawed.[6]

In the field of product design there have been a number of theoretical attempts focused on conveying meaning through design. Two such theories are the *theory of product language*[8] and *product semantics*,[9] both of these theories incorporate the concept of affordances into aspects of communication related to product use. The first theory, *product language,* was developed in Germany by Jochen Gros and Richard Fischer within the Hochschule für Gestaltung Offenbach. It states that a product has two types of semantic functions; one related to its symbolism (symbol functions) and another to its usefulness and usability (indicating or marking functions). Product markings function to communicate the nature of the product (i.e., type of product or category) and how it should be used.[8] In the United States, Klaus Krippendorff and Reinhart Butter proposed *product semantics*.[9] Their approach includes a theory of human interfaces, how users understand products and interact with them. Under their view, affordances are "building blocks" of the product interface with the capability of being perceived directly and effortlessly.[10]

3.2. Background

Regardless of how (or if) they are communicated, affordances offer actionable possibilities to the user (i.e., actor). In order to understand how to utilize the theory of affordances to enhance functionality in packaging, the following sections clarify and review key concepts with the objective of familiarizing the reader with the field in general and relevant theories.

3.2.1. Design principles

There are three design principles related to the perception of information that are critical for creating simple, usable package designs: principle of visibility,[11] signal-to-noise ratio,[12] and recognition-over-recall advantage.[13]

According to the *principle of visibility*, the usability of a product or system improves when possible actions (e.g., lift tab), and the subsequent result of the actions (e.g., to open), are clearly indicated by the design.[14] In the same way that written information on packages must be noticed to allow its mental processing,[11] specific, physical attributes of an object (e.g., the tab) must be clearly visible to the user and must convey precise messages (e.g., lifting this tab facilitates opening).[6] The features of a package must clearly communicate important information about how it functions and its current status.

The principle of visibility in design is a balancing act. On one hand, a package's perceptual information must clearly elicit the appropriate actions to accomplish a task with the packaging. However, excessive information has the potential to overwhelm users. This has been defined as *signal-to-noise ratio*, the ratio of relevant to irrelevant information.[12] Optimal designs present relevant information at the time it is needed and reduce the load on cognitive resources, making processing easy.

People are better at recognizing things they have previously experienced than recalling them, without cue, from memory. Recognition memory is accomplished through prior exposure; it is simply something has been experienced previously using the senses. Recall memory is achieved through memorization, practice, and application. This design principle is described as *recognition-over-recall advantage*.[13] Under this theory, perceptual information should provide recognizable cues to the users to minimize cognitive load.

3.2.2. Affordances: Design usefulness

Product designers have taken great interest in the concept of affordances because of the bridge it provides relating to a product's design, the interpretation of said design and, ultimately, its functionality. But there has only been limited, formal research that applies the concept to package design, despite the obvious potential benefits of the approach.[15] To consider the relationship between users and design features within packaging, the term affordance in this paper is used as Gibson[4, 5] proposed, but expanded to include the concept of perceptual information offered by Gaver[16] and McGrenere & Ho[17] (Fig. 3.1).

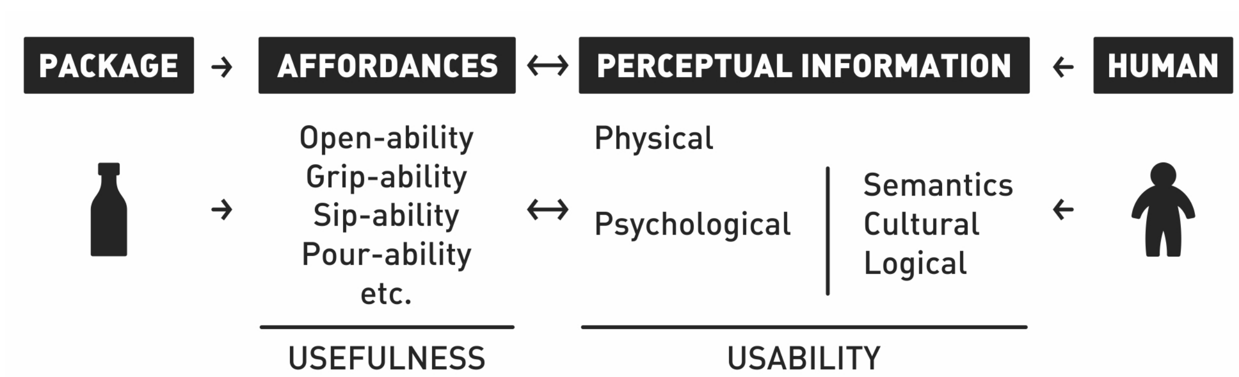

Figure 3.1 – Affordances and their perceptual information.
Adapted from McGrenere & Ho.[17]

Affordances are generally described with words ending with "-ability".[18] For example, the body of the package in Figure 3.2C affords "grasp-ability", its trigger affords "squeeze-ability", and the entire package affords the correct direction for "aim-and-shoot-ability". This conceptualization of affordances as general properties of an object is the basis for many affordance-based design approaches.[19-23]

The potential actions that design features enable, or "afford" users in the form of action, as well as the communication of these actionable possibilities, and the efficiency with which the design feature enables the task, ultimately determines the usefulness and usability of an object, in our case, a package.[17] Those who design with affordances in mind purposefully consider the actionable possibilities embedded in the design (usefulness). But the design must also communicate the appropriate actions to most users so they can effortlessly understand (usability). The challenge for designers is to specify perceptual information in ways that minimize cognitive demand, favoring direct perception.

Affordances allowed by packaging features can be communicated leveraging varied senses, including: vision, audition, and touch. Winder described the communication of the affordance by its signal of *strength* and *meaning*.[15] The strength of perceived affordances ranges from weak to strong. Weak affordances provide vague cues about how to operate an object, forcing users to focus on the task and use purposeful, effortful processing. The results of a package weakly communicating necessary actions to accomplish a task (e.g., the necessary removal a clear, tamper evident band by breaking small perforations located in a single location prior opening) include: inconvenience, frustration, increased time, embarrassment, and spills of contents, among others. By contrast, strong affordances are so evident that minimal cognitive resources are needed to intuit the proper actions of use (e.g., drinking from the orifice at the bottle's top).[15] In terms of *meaning*, affordances can be true or false.[15] False affordances are inefficient and mislead the user, resulting in inappropriate actions, while true affordances provide clues that, if followed, will enable the successful completion of the intended task (i.e., opening, closing, pouring, etc.).

3.2.3. Perceptual information: Design usability

According to Gibson's definition, affordances are specified by information.[4, 16, 17] This is, they are independent of perception, existing whether or not they are perceived. That said, in order to be effective, they must be communicated through the senses (perception) to suggest the possibility of action. An affordance that does not convey its existence through perception is defined as a "hidden affordance".[16] Affordances can also be misconstrued, conveying inappropriate actions. This is termed a "false affordance" and leads to an unsuccessful or inappropriate interaction.[16]

Interpretation of, and the definition for "perceptual information" varies. Galvao & Sato (2005)[19] classified it into two categories: *informative attributes,* which cognitively assist users in understanding product's functions, and *structural attributes,* which physically assist users in conveying appropriate physical actions (or affordances). The first group suggests behaviors using elements that derive meaning through purposeful cognition, like text and symbols, while the second type is a construct derived by physical characteristic such as form, color, material, and layout.

3.2.4. Constraints

One way to optimize the perceptibility of affordances is through the use of constraints. While affordances suggest a range of possible uses, actions, and functions of an object (in our case a package), constraints limit possible actions, guiding users to identify the proper use of an object.[6, 24] Well-designed constraints are most effective and functional when they are easy to perceive and understand so that restriction occurs prior to any action. Norman (1988) defined four different classes of constraints: physical, semantic, cultural, and logical.[6] Lidwell (2010) recognizes two kinds of constraints: physical constraints and psychological constraints.[24] Lidwell's criteria is conceptually similar to the one used by Galvao & Sato[19] described before, structural attributes and informative attributes.

Physical constraints rely on properties of the physical world (e.g., size, shape, weight, configuration, etc.) to limit the set of possible actions. This category includes constraints that redirect physical motion in specific ways by restricting possible operations.[6, 24] Physical constraints are generally used on packages. Examples include perforated or scored lines for ease of tearing, grip zones for enhanced grasping (Fig. 3.3C), sliders for ease of opening/closing on storage bags, tabs on lids for ease of pulling, etc.

Psychological constrains rely on the way people perceive and think about the world to limit the range of possible actions.[24] Examples are semantic constrains (i.e., symbols), cultural constraints (i.e., conventions), and logical constraints (i.e., mappings).

Semantic constraints rely on the meaning of the parts of a system to limit the range of possible actions. These types of constraints involve user's knowledge of the world to draw inference from known concepts and apply this inference to the existing design.[6] For example, the aerosol system depicted in Figure 3.3C conveys its operation (i.e., squeezing the trigger) by using a gun metaphor to convey the correct grip position and direction of spray. Semantic constraints are not limited to the physical; they may be further supported by things like symbols, warnings, and color that attempt to restrict possible actions by drawing inference from well-known concepts.

Cultural constraints rely upon accepted cultural conventions. Guidelines for cultural behavior are stored in peoples' minds as knowledge structures made of rules and information that help to interpret and to guide behavior.[6] A simple example of this in packaging is the continuous thread closure, even though there are physical constraints on them, the fact that users must rotate the cap counter-clockwise for opening and clockwise for closing is a cultural convention.

Logical constraints are driven by reasoning. They rely upon logical relationships to limit alternatives of operation. An example of this type of constraint is natural mapping in which there are logical relationships between a spatial or functional layout of components and the things that they affect or are affected by.[6] For example, to avoid the use of explicit labels and enhance ease of use, stove controls are arranged following a layout that resembles the arrangement of the burners (Fig. 3.2B). Consider the case of some child-resistant (CR) package designs in which users are required to push and turn the lid of a bottle. Before dealing with the physical effort of opening, users must understand first the logical sequence of operation. In CR packaging there are obvious physical constraints, which are invisible to the user, coupled with logical constraints that are explained by text on lids.

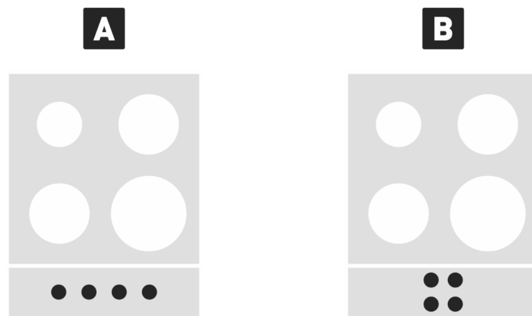

Figure 3.2 – Logical constraints for stove controls: which knob controls what burner? (A) Arbitrary arrangement, (B) Arrangement using natural mapping.

To illustrate how the concepts of affordance, perceptual information, and constraints work in tandem to impact package usability, consider the evolution of aerosol design. A typical task regarding an aerosol can is comprised of aiming and spraying at a specific target. In the early years of aerosols, there were very few affordances built in to the design to guide the user to the appropriate aim (Fig. 3.3A). The actuator afforded the action of downward pushing, which exposed the dip tube and dispensed the product. However, the constraints limiting the users to the appropriate direction of spray were non-existent (the actuator was flat). The only perceptual cue that could be utilized was the small orifice area on the actuator's front. As the design evolved, designers began to incorporate some of the concepts discussed herein into the design, enhancing the likelihood of appropriate spray direction. Generations of aerosols produced during the 1990s incorporated a small angle (physical constraint), coupled with an arrow indicating the appropriate direction of spray into the actuator (Fig. 3.3B). While an improvement, this was still quite subtle; the possibilities to target the spray remained numerous, including the potential unintended action (i.e., spraying the user themselves, a negative affordance). In more recent years, introductions, such as the Febreze® Air Effects® aerosol can (Fig. 3.3C), have taken the concept even farther. Its operation (i.e., squeezing the trigger) is conveyed by using a gun metaphor (semantic constraint). The trigger on the front affords squeezing (physical constraint) and the direction of use is constrained by this trigger and the plastic surface around the can's neck (physical constraint). This shape has geometrical characteristics such as a particular angle of inclination, a predominant axis of direction on the top, and a smooth decrease in diameter allows for only one power grip configuration in which the spray is naturally directed away from the user. Although all packages provide the user with strong affordances for either pushing down the actuator or squeezing the trigger to spray the package contents, differences in constraints differentiate packages with poor usability and one with enhanced usability.

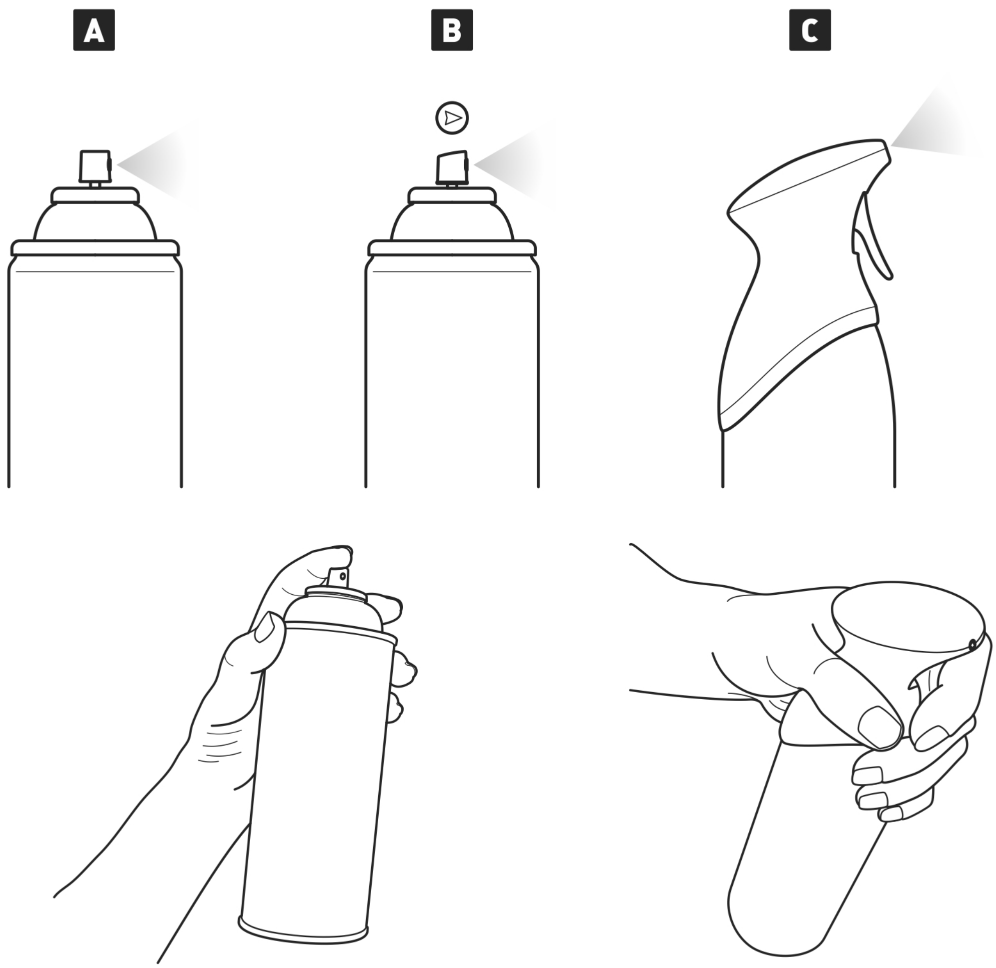

Figure 3.3 – Affordances and perceptual information of aerosol cans: (A) Early aerosol, (B) Modified aerosol, (C) Febreze® Air Effects®. Shape, materials, and configuration of each package suggest the use of a particular grip style.

3.2.5. Affordance-based design methods

Existing affordance-based design methods are cumbersome and oriented to complex products with mechanisms. Package designers and developers need a more convenient approach. There is a need for a practical, simple affordance-based method applied to structural and graphic design of packaging. Many insights gained from the design research community can be leveraged to develop a model to assist packaging designers.

Galvao & Sato (2005) [19] proposed three concatenated methods for linking product's technical functions, user's tasks, and affordances. Maier & Fadel (2009) [21] suggested a broad affordance-based design process that includes methods for documenting affordances, methods for designing individual affordances, an affordance-based method for reverse engineering and redesign, the affordance structure matrix, and affordance-based selection matrices. Hsiao *et al.* (2012) [25] proposed an affordance-based online tool to evaluate product usability in which a mathematical method is used for calculating affordance degrees. Authors claim that physical and online interaction yielded similar results and that the online method should be used instead of traditional evaluations to save time and costs. Their approach may be valid to evaluate some appearance features, but they failed to recognize an important limitation: an indirect visual interaction (i.e., users evaluating a product seen on a computer screen) is not the same as a real user-product interaction, with a physical product, in which all of the user's senses are involved.

3.3. Objectives

Our objective was to develop a method that can be used to evaluate package designs considering users, context of use, affordances, tasks, and packages' features.

3.4. Methodology

For a given package, the methodology consists of seven steps that can be included in a typical design process. They are as follows:

1) Identification of the context/s of use
2) Identification of patterns of use using a generic package use lifecycle
3) Identification of subtasks using ethnography
4) Identification of affordances using task analysis
5) Identification of perceptual information for each affordance
6) Diagnostic
7) Generation of alternatives for design solutions.

3.4.1. Identification of context/s of use

A package may be used in one or several contexts of use. Identification of these will facilitate the next steps.

3.4.2. Identification of patterns of use

A pattern of use is defined as a specific combination of one or more general tasks and it depends on user, package, and context of use. From purchasing through disposal, the interaction between a person and a package consists of series of tasks each involving a set of user’s actions. Figure 3.4 shows a generic package use life cycle to facilitate the analysis. The arrows indicate possible paths of action.

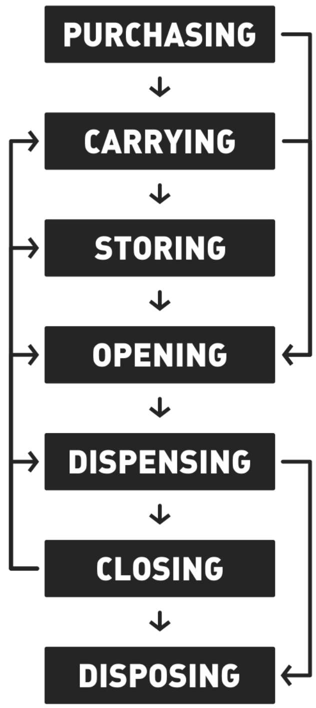

Figure 3.4 – Generic package use life cycle.

3.4.3. Identification of subtasks

Once that context of use and patterns of use have been identified, ethnographic research is used to observe, within the actual context of use, how users perform specific tasks. It is recommended that the same product trialing is carried out with different typical users and who are unfamiliar with the packaged product to test. Data collected in this step consist of video footing, audio, and notes.

3.4.4. Identification of affordances

Using the ethnographic data collected during step three, patterns of use are broken into a series of tasks (and subtasks) and task analysis is performed (see Table 3.1). For example, an opening task could be broken down in subtasks such as finding, gripping, pulling, and tearing. Each subtasks is then associated to an action possibility or affordance, as previously defined. Continuing with the opening example, this would translate in four affordances: find-ability, grip-ability, pull-ability, and tear-ability.

3.4.5. Identification of perceptual information

For each affordance identified in the previous step, one or more package features may be associated with it. The association between affordances and package features can be established by direct observation of users' actions and the package. Package features consist of physical and psychological perceptual information, as previously defined. The perceptual information involved has to be inferred from direct observation and by probing users after use.

3.4.6. Diagnostic

The analysis of the data collected in step three allows designers to evaluate a design in the hands of people. Usability problems will become visible during task analysis in the form of unintended subtasks, negative and false affordances, or even the impossibility of task completion. All these issues are linked to problematic package features that designers can improve and change as needed.

3.4.7. Generation of alternatives for design solutions

Once issues have been identified, package designers are skillful at generating design solutions within other types of constraints related to manufacturing, cost, packaging line, etc. The methodology is repeated until tasks are performed smoothly by the vast majority of the users.

3.5. Case study: A package containing a syringe and a vial

3.5.1. Background information

To demonstrate the use of the proposed method, we present a case study centering on a product that is typically used by nurses, physicians, and paramedics in emergency situations to treat severe allergic reactions, including anaphylaxis. The product consists of a folding carton (l=48 mm, w=26 mm, d=142 mm) containing a plastic syringe and a glass vial filled with a liquid drug (Fig. 3.5). Due to the short length of the glass vial, internal paperboard dividers hold it to provide its easy access from one carton's end (Fig. 3.6). For that reason, the package must be opened from a specific end of the carton (Fig. 3.5A) by pressing two triangular flaps located on one side of the package, while simultaneously grabbing the end flap and pulling it from the carton. Both scores that traverse the length dimension of the carton are perforated to facilitate the complete removal of the end flaps and then the contents. The opposite end has glued flap and is not intended to be opened (Fig. 3.5B). The front of the package has general information about the product while the back has instructions for using an aseptic technique to assemble the syringe, needle, and vial.

Figure 3.5 – Folding carton containing a syringe and a vial used as case study.
(A) Carton's end intended for opening, (B) Opposite end with glued flaps.
(For interpretation of the references to color in this and all other figures, the reader is referred to the electronic version of this dissertation).
(Note: Text on the packages is irrelevant).

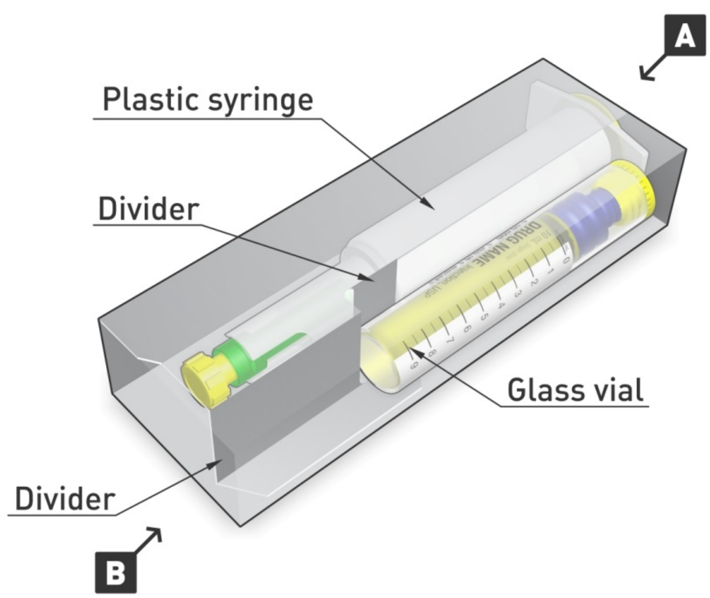

Figure 3.6 – Internal component's layout. Notice the two vertical dividers blocking the access of the contents in one end (B). (Note: Text on the vial is irrelevant).

3.5.2. Methodology

3.5.2.1. Identification of context/s of use

This product is used in situations where time is critical; typical locations include:

- Emergency rooms
- Ambulances
- Operating environments

3.5.2.2. Identification of patterns of use

Patterns of use were identified for the three context of use:

- Emergency room: storing, opening, dispensing, disposing
- Ambulance: storing, opening, dispensing, disposing
- Operating environment: storing, opening, dispensing, disposing

3.5.2.3. Identification of subtasks

An ethnographic observational study in a specific context of use is performed to collect data. This data is then analyzed using task analysis techniques. For example, one trial can be summarized as follows. A person first opened the package from the top end (Fig. 3.5B) by completely tearing off the glued flaps. The internal dividers within the carton (Fig. 3.6) obstructed access to both the vial and syringe. Then, the person opened it from the other end by tearing apart the bottom flaps (Fig. 3.5A). Once opened, the person got access to the contents. Table 3.1, second column, details the subtasks identified (times for each task are not shown but they could be included).

3.5.2.4. Identification of affordances

Each subtask identified in the previous step may be associated with an "action possibility", affordance (Table 3.1, column 3).

3.5.2.5. Identification of perceptual information

For each affordance identified in the previous step, one or more package features were associated by direct observation (Table 3.1, column 4). Perceptual information was identified by analyzing those package features and inferred from watching user actions and probing them with questions after completion of the tasks.

Table 3.1 - Identification of pattern of uses, subtasks, affordances, and possible perceptual information at play for one subject trial.

Pattern of Use	Subtask	Affordance	Folding Carton Design Feature	Possible Perceptual Information
Storing	Finding the package	Find-ability	All sides	Color, text, package shape
	Grabbing the package	Grip-ability	All sides	Package shape
	Looking for space to grip	Grip-ability	Body	Package shape
	Grabbing the package with one hand	Grip-ability	Body	Package shape

Table 3.1 (Cont'd)

Pattern of Use	Subtask	Affordance	Folding carton design feature	Possible Perceptual Information
Opening	Finding place to open	Find-ability	Body	Text orientation
			Top end	Top flap's edges and corners (Fig. 3.5B)
	Tearing off the top flap of the top end	Tear-ability	Top end	Top flap's edges and corners (Fig. 3.5B)
	Folding out inner flaps	Fold-ability	Top end	Inner flaps
Dispensing	Trying to grab syringe or vial		Inside	Inner division obstructing access
			Inside	Visual of vial and syringe
Opening	Finding place to open	Find-ability	Bottom end	Perforated edges
			Side panel	Legend "OPEN"
			Front panel	Arrow and legend "PRESS AND PULL TO OPEN"
	Pressing with finger	Press-ability	Side panel	Folding triangular flaps (Fig. 3.5A)
	Grabbing bottom end flap	Grip-ability	Bottom flap	Flap's surface (Fig. 3.5A)

Table 3.1 (Cont'd)

Pattern of Use	Subtask	Affordance	Folding carton design feature	Possible Perceptual Information
Opening (cont'd)	Pulling off flap	Tear-ability	Bottom flap	Perforated edges
	Discarding flap		Bottom flap	
Dispensing	Dumping contents on hand	Dump-ability	Opened end	Package shape

3.5.2.6. Diagnostic

User trialing showed that the product described above has a number of issues that make its use problematic. They are as follows:

- *Semantic constraint*: although the general package shape affords grabbing it leaving only two possibilities for opening (i.e., both ends), the text orientation on the front panel may suggest to some users a package's vertical orientation that defines a top and a bottom end. When this happens the opening feature is located on the bottom of the package; this is counter-intuitive for an opening action. In general, products are opened from the top.
- *Negative affordance*: the flap on one of the ends (Fig. 3.5B) affords opening in a place that will not allow access to the package contents. It guides the user to inappropriate opening because this end is obstructed by the internal dividers and it is not possible to access to the contents.
- *Hidden affordances*: the actual opening mechanism is not clearly visible (*principle of visibility*). Moreover, its perceptual information does not

communicate well how it functions; it does not provide good recognizable cues (*recognition-over-recall advantage)*.

- *Signal-to-noise ratio:* when physical perceptual information for an affordance is not perceived, psychological information such as the arrow and the opening legends may help to communicate to the user what to do. However, the ratio of relevant to irrelevant information for opening seems compromised. Written information on this panel is lacking visual hierarchy and as a result the legend indicating where to open, placed at the bottom of the front panel, is not obvious.

3.5.2.7. Redesign

There are several design solutions to improve the package system tested. One solution is shown in Figure 3.7; it uses a similar carton blank surface area (Fig. 3.8) to the original design. The redesign includes the following changes:

- Rotation of the front panel text by 180 degrees so the package's opening mechanism is on the top end (Fig. 3.7A). This change will suggest users to hold the package in the right orientation.
- Addition of foldable tab for pulling and tearing on the top end (Fig. 3.7A). This end keeps the original perforated feature. Opening written instructions on the front panel have been removed to avoid confusions; the added tab has an arrow and a legend (i.e., TEAR) as additional directions. This change will provide a better affordance for opening the carton.
- Minimization of visible edges and corners on the bottom end so it does not afford openability (Fig. 3.7B). This change will reduce the likelihood of inappropriate opening.

Figure 3.7 – Redesigned package.
(Note: Text on the packages is irrelevant).

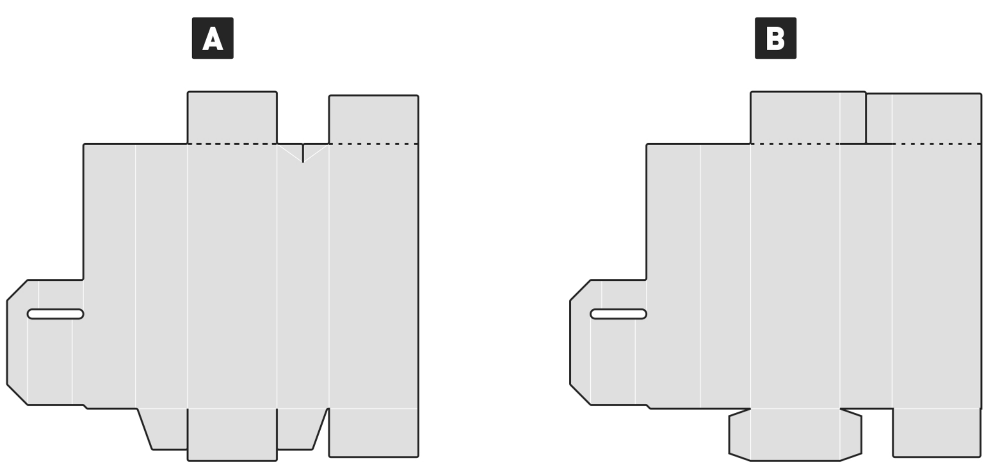

Figure 3.8 – Comparison of the two blanks.
(A) Original, (B) Redesign.

3.6. Conclusions and discussion

Our review of the literature regarding human-package interaction suggests a gap in the research investigating perception and cognition as it relates to packaging use. We believe that the concept of affordance can be used to produce innovations in this regard and to enhance functionality in packaging. This research introduced the main concepts of the theory of affordances with specific reference to packaging design applications and proposed a novel approach. As current affordance-based approaches to design are cumbersome to use and focus on the design of complex products, a straightforward, affordance-based design methodology is proposed. The method relates tasks, affordances, and package's features for specific users and contexts of use. It is intended to explore and evaluate package designs and provides a useful tool for package developers (i.e., marketers, designers, and engineers) so that they can purposefully consider affordances during the design process to improve package usability. A step-by-step case study is presented to illustrate the process.

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4

Relationship between peel angle and peel force in peelable semi-rigid packaging

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Abstract

Testing standards such as ASTM F88 and ASTM F2824 acknowledge the effect of peel angle on peel force during package opening. However, the literature does not provide mathematical relationships between peel angle and force. This research aims to fill this gap. Experimental peel force measurements were collected for two testing conditions (A and B) at varied peel angles every 15° intervals. Testing conditions had different seal geometries and peel directions. In condition A, the tray was completely sealed. In condition B, the tray was partially lidded and the sealed areas were comprised of two parallel rectangular seals. The peel angle range for condition A was 0-135° and for condition B was 0-90°.

Experimental data for force vs. angle for both conditions followed a U-shaped pattern with minimum values at peel angle 45°. For condition A, beyond 90° peel forces increased rapidly and it is hypothesized that for peel angle equal to 180° force will tend to infinity and no peeling will be produced. Statistical analysis of the 0-90° range suggested four homogenous subsets (i.e., peel angle ranges) that resulted in statistically differing forces. For testing condition A, the lowest forces resulted when peel angle was 45° for average force and between 45-75° for peak force. For condition B, lowest forces resulted when peel angle was between 30-45° for both average force and peak force.

Classical mechanics was then used to derive an equation in which peel force is a function of peel angle. Two approaches were taken to fit the data to this equation: linearization and nonlinear regression. When fitting the equation over the 0-90° peel angle range, minimum force values were predicted to occur between 45° and 50°, which matched the experimental data.

Key words

Peelable seal, peeling, packaging design, usability, mathematical modeling, peel angle, peel force, lidded trays

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4.1. Introduction

The American Society for Testing and Materials (ASTM) defines a flexible material as a material with a flexural strength and thickness allowing a fold at an approximate 180° angle [1]. Based on the flexibility of each of the two components of a heat sealed seal, packages can be classified into two broad categories:

a) Flexible packages: both sides of the seal are made of flexible material. Examples include bags, envelopes, pouches, sachets, wraps, flexible thermoformed films, etc.
b) Semi-rigid packages: only one side of the seal is flexible. Examples include induction seals on bottle finishes, trays, bowls, cups, pots, etc.

This article deals with the openability of a tray with peelable lids containing tabs (i.e., a semi-rigid system). In this type of package, a tab is typically used to enable people to overcome seal forces. The tab becomes a tool to exert a pulling force sufficient to separate the lid stock from the tray (either an adhesive or cohesive failure at the seal interface). Pulling direction can be defined by two angles, α and β. Both angles are shown in Figure 4.1, α is the angle between the peel force $\vec{P}$ and the plane defined by the seal, β is the angle between the projection of $\vec{P}$ on the lid and a line parallel to the longest tray's edge. In other words, α is defined as the "peel angle" and β as the "peel direction angle".

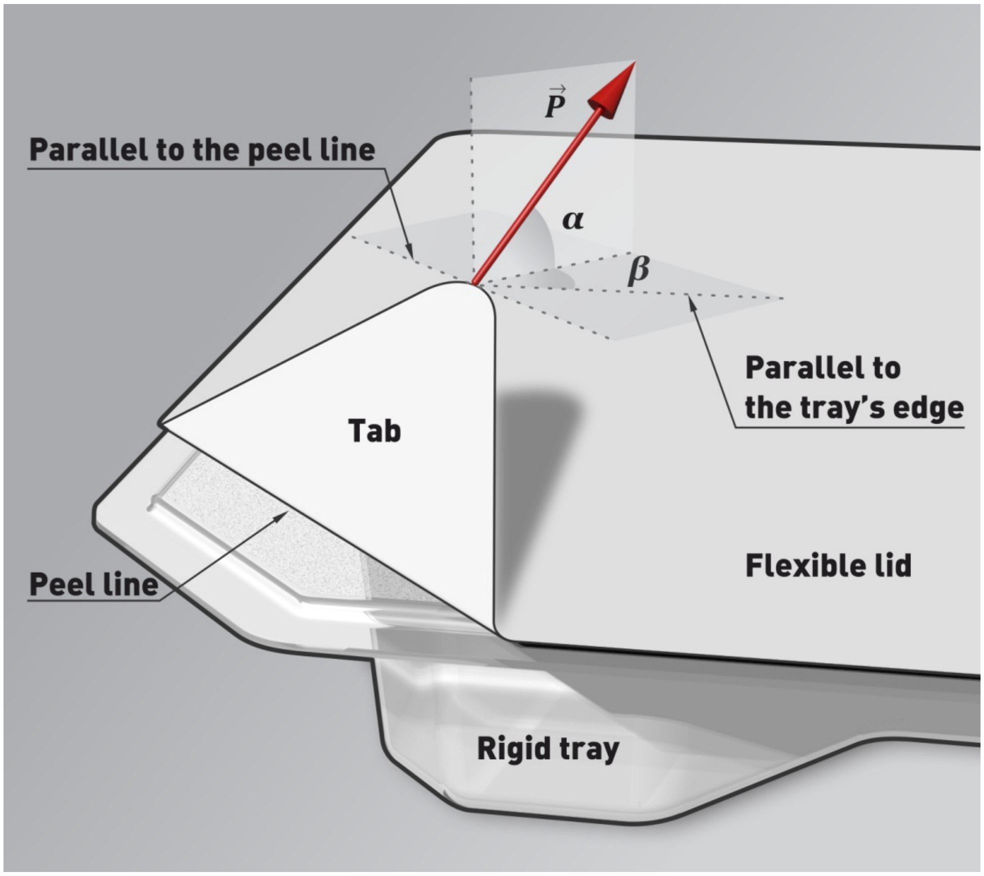

Figure 4.1 – Peel force and peel angles of a tab.

There are two standards that acknowledge the effect of peel angle on peel force but do not provide mathematical relationships or references regarding the relationship between peel angle and force. One is the "Standard Test Method for Seal Strength of Flexible Barrier Materials (ASTM F88)" which describes a procedure to measure the force required to separate a test strip of material containing the seal [1]. The test is intended to measure peel strength between two flexible materials; it is not appropriate to test lidded trays (i.e., semi-rigid packages) tested herein. The standard recognizes three tail holding methods: Unsupported, Supported 90°, and Supported 180° (Fig. 4.2).

In the first case, the angle α between the direction of pulling and the tail of the sample is unknown because the tail moves freely during testing. In the supported 90° method, the tail of is held by hand at an approximate angle of 90°. In the supported 180° method, an alignment plate keeps α equal to zero.

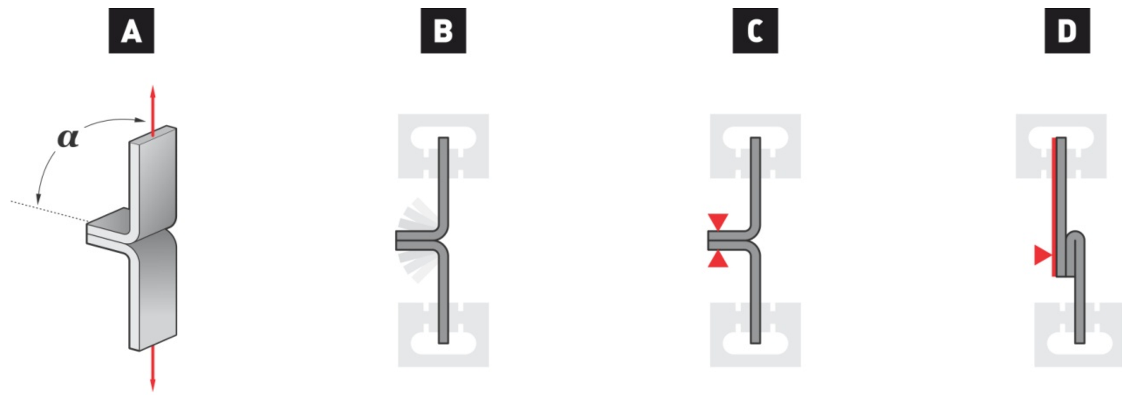

Figure 4.2 – ASTM F88 sample and tail holding methods: A) Seal sample schematic, B) Unsupported, C) Supported 90°, D) Supported 180°.[1]

The second standard procedure is called "Standard Test Method for Mechanical Seal Strength Testing for Round Cups and Bowl Containers with Flexible Peelable Lids (ASTM F2824) [2]. This test method is used to determine the continuous and maximum forces required to separate the lid from the container. It uses an angle of pull of 45° but also suggests that other angles may be used. It is not explained why 45°.

With regard to packaging applications, Nase *et al.* (2008) used environmental scanning electron microscopy to investigate the micro deformations of seals of low density polyethylene / isotactic polybutnen-1 (LDPE/iPB-1) during peeling. This study concluded that peel angle is related to the failure mechanism of the seal. Specifically, the researchers suggested that for peeling angles between 70° and 120°, the crack propagation is *interlaminar* (i.e., the crack grows along the center of the seal) while for peeling angles between 140° and 180° the crack propagation is *translaminar* (i.e., the crack grows over the cross-section of the film) [3].

A recent article by Liebmann *et al.* (2012) pointed out the need for more systematic research on the forces required to open peelable packaging as well as the forces that consumers are actually able to exert. The authors recognize the importance of peeling angle during opening. However, they do not report systematic data or equations to describe the relationship between peel angle and peel force [4].

In the field of adhesive tapes, a "peel test" is commonly used to determine the strength of adhesive joints. Several mathematical and physical models have described the effect of peel angle on peeling force during tape peeling [5-9]. This work suggests that peeling tests using tape are affected by a number of factors, such as: the angle at which the adhering tape is detached, the rate of detachment, the nature of the solid surface to which the tape is bonded (substrate), the mechanical and physical properties of the backing and the adhesive [5]. It seems reasonable that there might be similarities between tape peeling and packaging peeling. However, limited information about whole package seals is available and these relationships have yet to be established.

4.2. Objectives

On the basis of the described limitations of the existing scientific literature and standard test methods, there is a need to investigate and describe the relationship between peel angle and peel force in order to optimize the functionality of lidded trays.

4.3. Materials and methods

4.3.1. Procedure

The force needed to completely peel the lid off of sealed trays was measured using a universal tensile testing machine (Instron Inc., Norwood, MA) at a rate of 12 in/min (300 mm/min). There were two testing conditions with different seal geometries and peel directions. In condition A, the tray was completely sealed (Fig. 4.3). In condition B, the tray was partially lidded and the sealed areas consisted of two parallel rectangular seals (Fig. 4.4). Each sealed tray was secured to a custom-made variable angle fixture (Fig. 4.5) at specific positions (α and β) using a wing nut (size 10-24 type A). Peak force, average force, and peel extension were recorded for both conditions. Condition A was tested using a β=45° and ten values for α (0, 15, 30, 45, 60, 75, 90, 105, 120, and 135 degrees). Condition B was tested using a β=0° and seven values for α (0, 15, 30, 45, 60, 75, and 90 degrees). Five replicates of each of the 17 measurements were conducted; as such, a total of 85 lidded trays were tested.

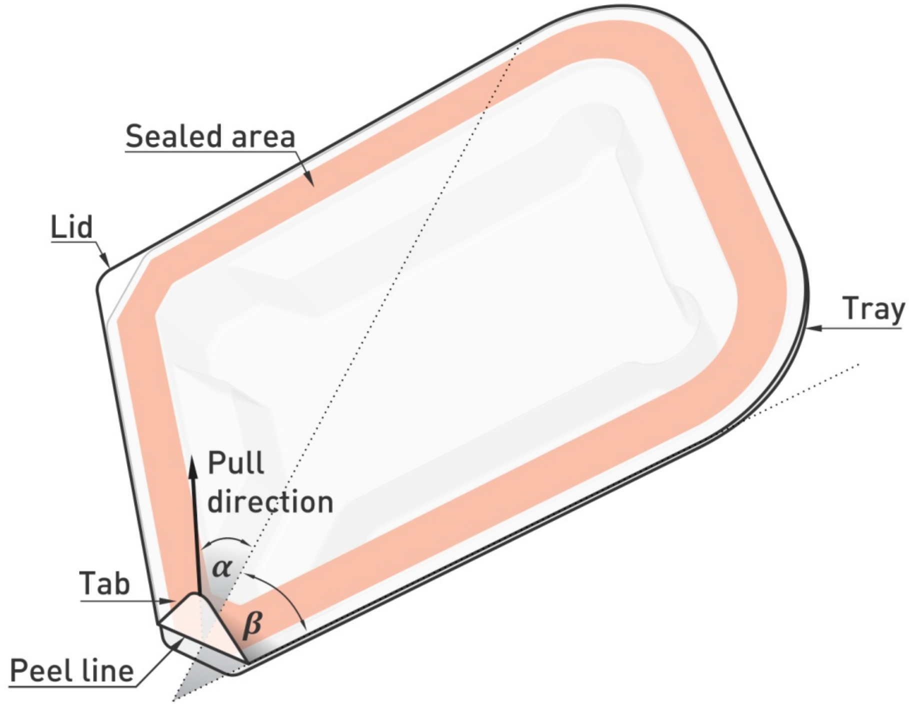

Figure 4.3 – Condition A: Lidded tray tested at β=45° and α=0-135° (shown at α=45°). Sealed area shown in red.

Testing Condition A (Fig. 4.3) allowed examination of peel force variation at different peel angles in a scenario with variable peel widths and peeling an entire tray. Testing condition B (Fig. 4.4) enabled examination of the relationship under a constant peel width in a partially lidded tray.

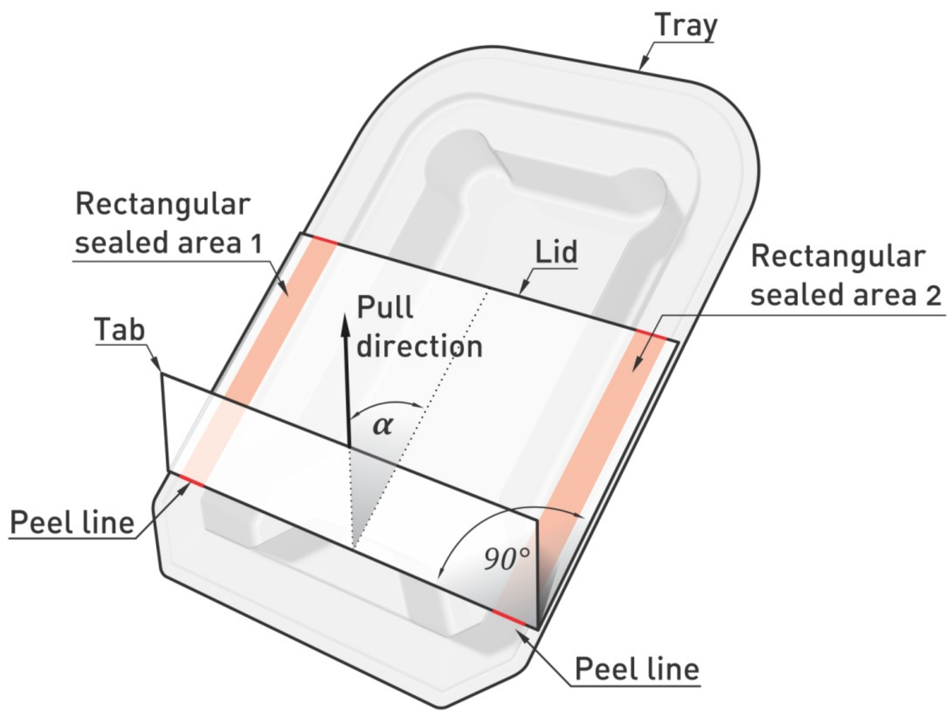

Figure 4.4 – Condition B: Partially lidded tray with two rectangular sealed areas (in red) tested at β=0° and α=0-90° (shown at α=45°).

4.3.2. Packages

Trays were thermoformed from a blue tint uncoated PETG, preform thickness of 0.025 inches using the mold "Medtronic Inc. outer tray part number 350215-001" (Perfecseal, Oshkosh, WI). Trays were sealed with PTH-017 seal coated 1073B Tyvek® die cut lids (Amcor Flexibles Healthcare, Madison, WI) using a CeraTek MD-2420 shuttle-style heat sealer (SencorpWhite, Hyannis, MA). In order to temporarily fix the trays to the fixture, each had a 3/16 in hole drilled in the center of its bottom. Through this hole it was affixed to a rectangular piece of plywood (thickness ¼ in × width 2 in × length 3.5 in) that held the bottom of the tray flat against the fixture using a round machine screw (size 10-24 × length ¾ in) prior to sealing. For condition B, after being sealed, part of the lid was removed resulting in a 25 mm tab with 76 mm of straight seals intact (Fig. 4.4).

4.3.3. Heat sealing

The heat sealer temperature was 150°C, the pressure was 70 psi, and the cycle time 3 seconds. After sealing, trays were visually inspected for defects according to ASTM F1886 Standard Test Method for Determining Integrity of Seals for Medical Packaging by Visual Inspection [10]. Trays with visible defects were removed. Each tray was identified by a code made up of a sealing position (from A, top left cavity, throughout I, bottom right cavity) and run number.

4.3.4. Variable angle test fixture

The variable angle test fixture (Fig 4.5) was designed and built so that it holds the tray such that angles α and β are maintained throughout testing. The fixture consists of a ramp attached to a cart with wheels that kept the sample vertical while peeling. A protractor allows the platform to be fixed at seven positions in 15-degrees intervals, from 0 through 90 degrees. The tray is bolted to the platform, and a special gripping device grips the tray tab with upper jaw of the tensile testing machine. As the crosshead moves vertically, the cart moves along a rail, maintaining a constant angle during peeling.

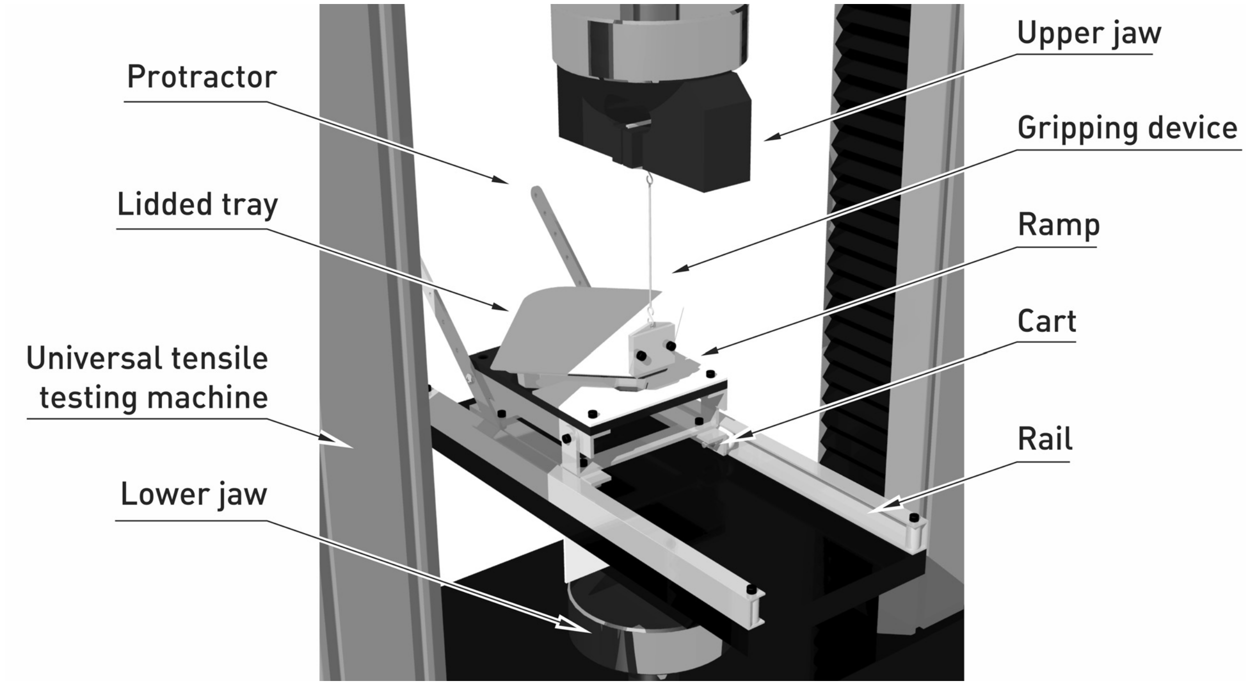

Figure 4.5 – Variable angle test fixture.

4.3.5. Data analysis

The data were analyzed using SPSS version 16 [11] and SigmaPlot™ version 9 [12].

4.4. Results

4.4.1. Condition A

The peak and average forces of 50 trays were measured for 10 values of α with β fixed at 45 degrees (Fig. 4.1 and Table 4.1). A typical Force *vs*. Distance plot (obtained for each of the 50 specimens) is shown in Figure 4.6. Distance is the vertical distance traveled by the upper jaw of the tensile instrument. Peak force is the highest force measured during the test. Average force was calculated using data only from the central 80% of the curve as ASTM F88 suggests (marked by the two black vertical lines in Fig. 4.6). This might not be meaningful for testing a whole seal but it is when testing condition B.

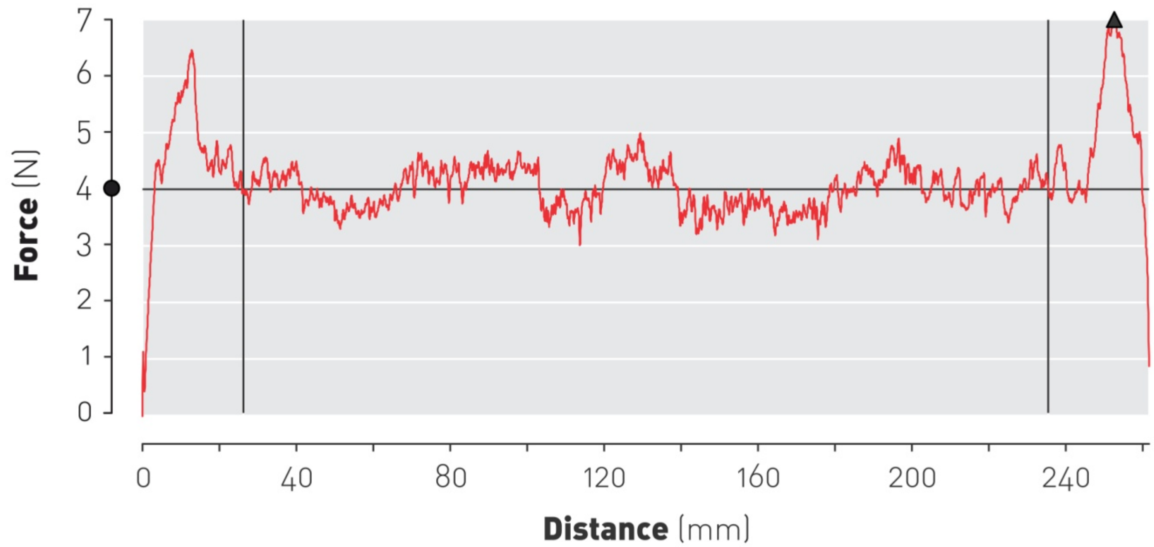

Figure 4.6 – Example of a Force *vs*. Distance plot for a tray opened at α=60° and β=45°. (▲) Peak force, (●) Average force.

Peel force is affected by the width of the peel lines (W_1 and W_2 in Fig. 4.7). The peel line is defined by a section of the tray's land area perpendicular to the peel line. Peak forces occurred where the peel line was widest.

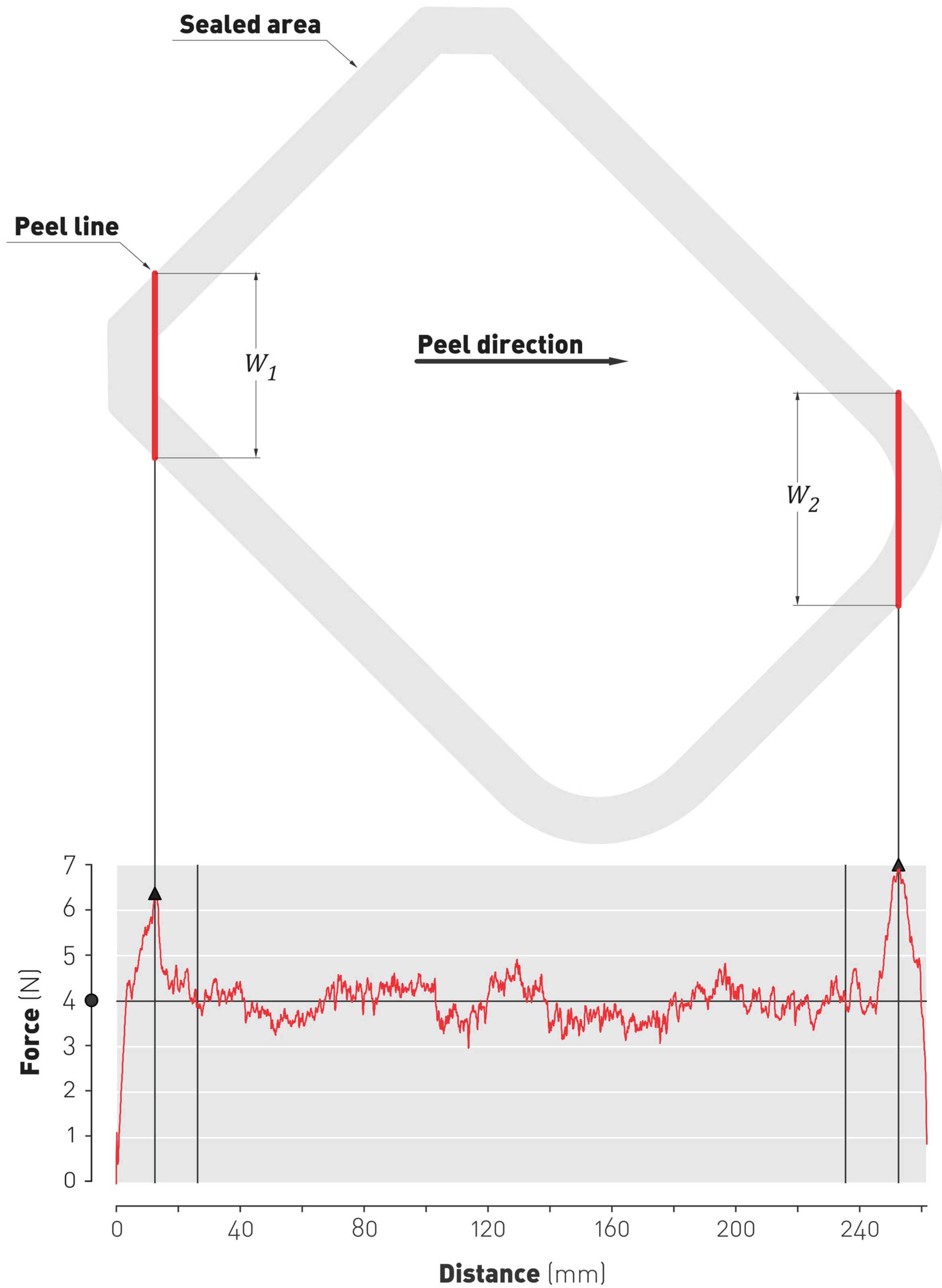

Figure 4.7 – Condition A: Relationship between peak forces and peel line widths (W_1 and W_2).

The data suggest an effect of peel angle on peel force (Table 4.1). For both forces, peak and average, the minimum peel force occurred at around α=45° (Fig. 4.8). At angles close to α=0°, when the tab is completely folded back against the lid, peak forces increased by 75% and average force by 59% when compared with the peel force at α=45°. At α=90°, the tab and lid form a right angle, and the peak force increased 58% and average force increased 45%. Beyond 90° peel forces increase rapidly. It is hypothesized that for α=180° the force will become so large that the material will break before it peels.

Table 4.1 – Condition A: Mean peak and mean averages forces required to peel off a lidded tray at α=0-135° and β=45°.

β (Deg)	α (Deg)	Mean Peak Force (N)			Percent Difference with Minimum Peak Force (%)	Mean Average Force (N)			Percent Difference with Minimum (%)
45	0	10.43	c	± 0.86	75	6.05	d	± 0.37	59
45	15	7.32	b	± 1.00	23	3.91	b	± 0.84	23
45	30	7.22	b	± 0.35	21	4.09	b	± 0.21	26
45	45	5.95	a	± 0.39	-	2.54	a	± 0.19	-
45	60	6.98	a,b	± 0.25	17	3.82	b	± 0.20	21
45	75	7.08	a,b	± 0.31	19	3.86	b	± 0.35	22
45	90	9.39	c	± 0.23	58	5.23	c	± 0.20	45
45	105	9.72		± 0.71	63	5.11		± 0.90	43
45	120	16.01		± 1.42	169	6.84		± 0.61	72
45	135	24.85		± 1.01	317	9.29		± 2.23	113

[a,b,c,d] : Groups statistically significant different from one another ($p<0.05$).

A one-way ANOVA comparing mean peak forces and average forces at peel angles from 0° through 90° (the range relevant to packaging peeling) was done. A significant difference was identified for peel angles for both peak force ($F(6,28)=38.076$, $p<0.05$)) and for average force ($F(6,28)=39.516$, $p<0.05$)). Tukey's HSD was used to make pair-wise comparisons of peel angle data. This analysis revealed three homogenous subsets for peak force. One group included peel angles of 45°, 60°, and 75°. A second group comprised 15°, 30°, 60°, and 75° and the third group included 0° and 90°. For average force, the post-hoc analysis exposed four homogeneous subsets. The first group had the lowest force including only peel angle of 45°, the second group included peel angles 15°, 30°, 60°, and 75°, the third group included only peel angle of 90°, and the fourth only 0°.

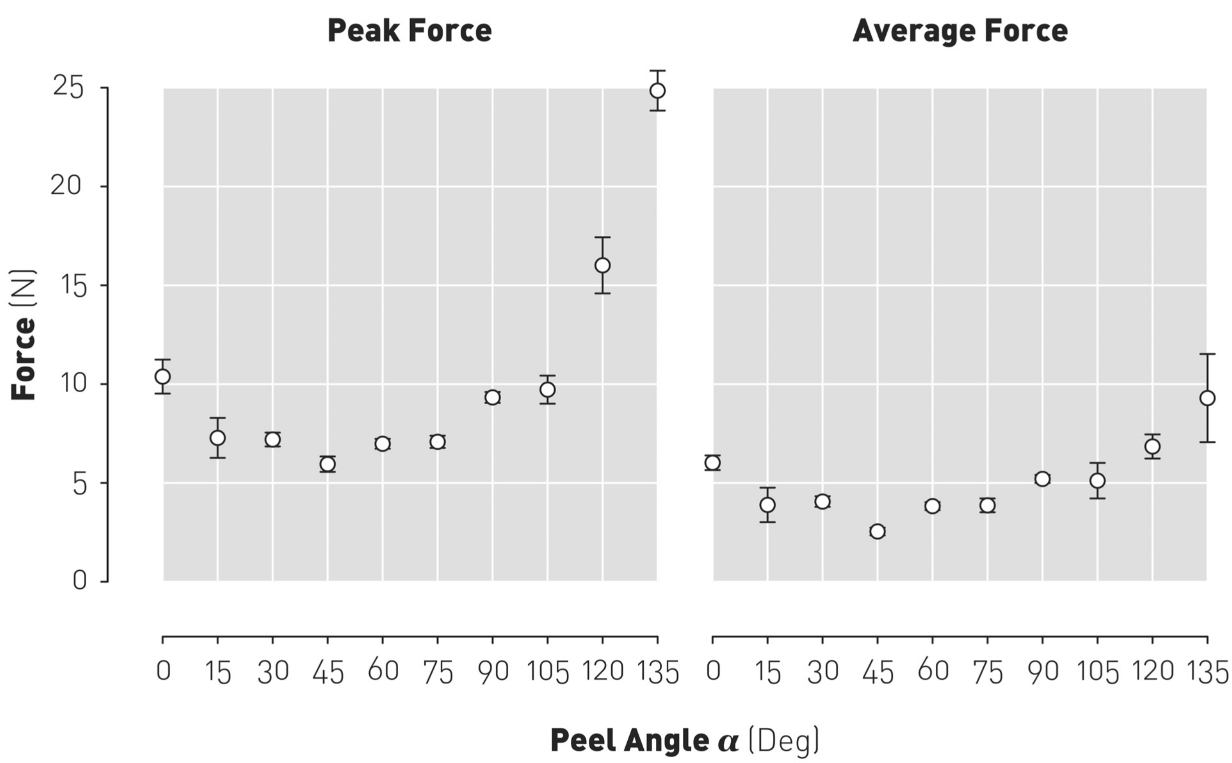

Figure 4.8 – Condition A: Mean force *vs*. peel angle α.

4.4.2. Condition B

A total of 35 trays were tested to measure peak and average forces for 7 values of α with β fixed at 0° (Fig. 4.9 and Table 4.2). As for condition A, peak and average forces were found to be a minimum at α=45°. At peel angles close to α=0° peak forces increased by 76% and average force by 71% with respect to the minimum force at α=45°. At an angle α=90°, the tab and lid form a right angle, and the peak force increased 56% and average force increased 53%.

Table 4.2 – Condition B: Mean peak and mean averages forces required to peel off a tray partially lidded at α=0-90° and β=0°.

β (Deg)	α (Deg)	Mean Peak Force (N)	Percent Difference with Minimum Peak Force (%)	Mean Average Force (N)	Percent Difference with Minimum Average Force (%)
0	0	4.88 [d] ± 0.42	76	4.03 [d] ± 0.38	71
0	15	3.58 [b] ± 0.15	29	2.94 [b,c] ± 0.10	32
0	30	3.27 [a,b] ± 0.33	18	2.68 [a,b] ± 0.31	22
0	45	2.78 [a] ± 0.25	0	2.06 [a] ± 0.26	0
0	60	3.57 [b] ± 0.47	29	2.96 [b,c] ± 0.44	33
0	75	3.85 [b,c] ± 0.33	39	3.08 [b,c] ± 0.38	37
0	90	4.33 [c,d] ± 0.31	56	3.52 [c,d] ± 0.44	53

[a,b,c,d] : Groups statistically significant different from one another ($p<0.05$).

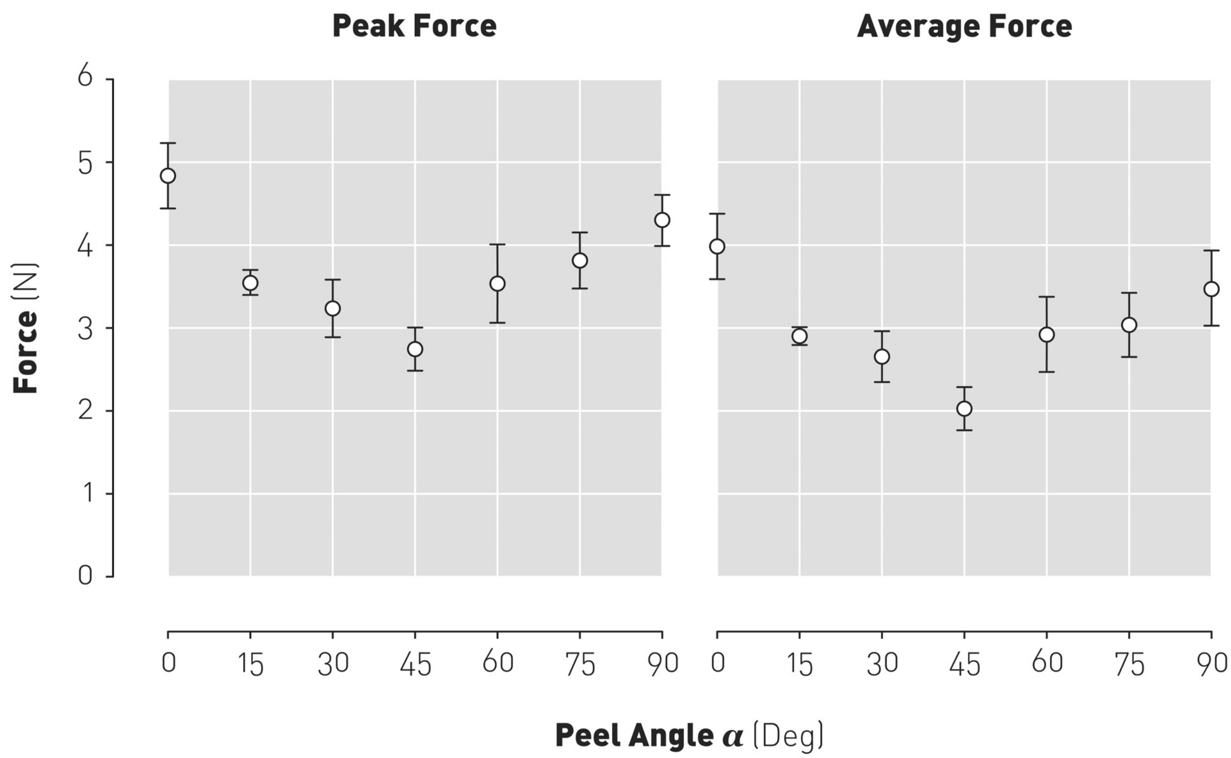

Figure 4.9 – Condition B: Mean force *vs*. peel angle α.

A one-way ANOVA comparing mean peak forces and average forces at peel angles from 0° through 90° was done. A significant difference was found among peel angles for both peak force ($F(6,28) = 21.312$, $p < 0.05$)) and average force ($F(6,28) = 15.963$, $p < 0.05$)). Tukey's HSD was used to determine the nature of the differences between peel angles. This analysis revealed four homogenous subsets for peak force. The first group had the lowest forces including peel angles 30° and 45°, the second group included peel angles 15°, 30°, 60°, and 75°, the third group included peel angles 75° and 90°, and the fourth 0° and 90°. For average force, the post-hoc analysis revealed four homogeneous subsets. One group included peel angles of 30° and 45°. A second group included 15°, 30°, 60°, and 75°. The third group included 15°, 60°, 75°, and 90°. The fourth group includes peel angles 0° and 90°.

4.5. Curve fitting

Classical mechanics was used in an attempt to explain the experimental data. Consider the system of forces shown in Figure 4.10. *P* is the peel force.

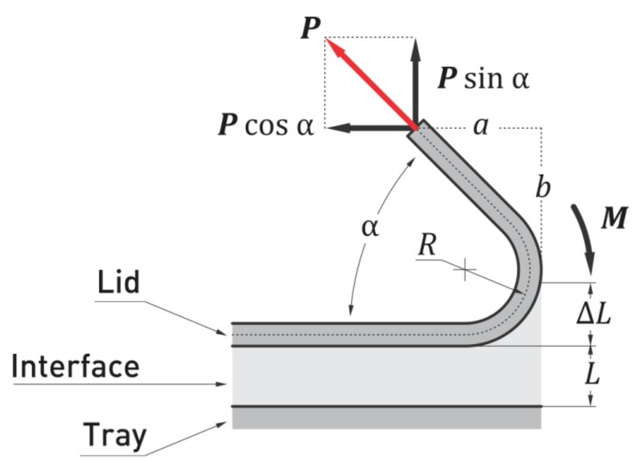

Figure 4.10 – Theoretical system of forces acting at the peel line.

A free body diagram of that portion of the lid that is no longer attached to the tray is shown on the right in Fig. 4.10. The vertical stretch ΔL of the adhesive at the edge of the peel line is due to:

1) The lifting effect of $P \sin \alpha$
2) The counterclockwise twisting effect of the bending moment M
3) No effect of the horizontal shearing force $P \cos \alpha$

Assuming that these effects are additive and that each effect is proportional to P

$$\Delta L = C_1 P \sin\alpha + C_2 M \quad (1)$$

$$M = bP\cos\alpha - aP\sin\alpha \quad (2)$$

Substitution of Eq. 2 into Eq. 1:

$$\Delta L = C_1 P \sin\alpha - C_2 aP\sin\alpha + C_2 bP\cos\alpha \quad (3)$$

$$\Delta L = (C_1 - C_2 a)P\sin\alpha + C_2 bP\cos\alpha \quad (4)$$

$$\Delta L = C_3 P\sin\alpha + C_4 P\cos\alpha \quad (5)$$

$$\Delta L = P(C_3\sin\alpha + C_4\cos\alpha\ ) \quad (6)$$

C_1, C_2, C_3, and C_4 are functions of the thickness and modulus of elasticity of the lid (these determine the radius of curvature R at the bend), the modulus and thickness of the adhesive, P, and α. For a first order approximation we can assume C_1, C_2, C_3, and C_4 to be constant (equivalent to assuming they are weak functions of α). Assuming that the interface breaks at the peel line when the strain there, $\Delta L/L$, reaches a break point strain ϵ_{BP}:

$$\epsilon_{BP} = \frac{\Delta L}{L} \qquad \text{Break point strain} \quad (7)$$

$$\epsilon_{BP} = \frac{P(C_3\sin\alpha + C_4\cos\alpha)}{L} \qquad \text{Substitution of Eq. 6 into Eq. 7} \quad (8)$$

$$P = \frac{1}{\frac{C_3}{\epsilon_{BP}L}\sin\alpha + \frac{C_4}{\epsilon_{BP}L}\cos\alpha} \qquad \text{Solving Eq. 8 for } P \quad (9)$$

Peel force vs. α

$$P = \frac{1}{k_1 \sin\alpha + k_2 \cos\alpha} \tag{10}$$

Where k_1 and k_2 are constants for a given lidded tray system

Two approaches were taken to fit Equation 10 to the data: linearization and non-linear regression.

4.5.1. Approach 1: Linearization

One way to fit Eq. 10 to the experimental data is to linearize it with respect to k_1 and k_2

$$k_1 \sin\alpha + k_2 \cos\alpha - \frac{1}{P} = 0 \qquad \text{Linearized Eq. 6} \tag{11}$$

Now k_1 and k_2 are chosen so that the sum of squares of errors (SSE) is a minimum:

$$SSE = \sum_{i=1}^{n} \left(k_1 \sin\alpha_i + k_2 \cos\alpha_i - \frac{1}{P_i}\right)^2 \tag{12}$$

$$\frac{dSSE}{dk_1} = \sum_{i=1}^{n} 2(\quad)' \sin\alpha_i = 0 \Longrightarrow \sum_{i=1}^{n} \frac{\sin\alpha_i}{P_i}$$
$$= k_1 \sum_{i=1}^{n} \sin^2\alpha_i + k_2 \sum_{i=1}^{n} \sin\alpha_i \cos\alpha_i$$

for
)

$$\frac{dSSE}{dk_2} = \sum_{i=1}^{n} 2(\quad)' \cos\alpha_i = 0 \Longrightarrow \sum_{i=1}^{n} \frac{\cos\alpha_i}{P_i} = k_1 \sum_{i=1}^{n} \sin\alpha_i \cos\alpha_i + k_2 \sum_{i=1}^{n} \cos^2\alpha_i \tag{14}$$

$$k_1 = \frac{S_1 S_5 - S_2 S_3}{S_1 S_4 - {S_2}^2} \tag{15}$$

$$k_2 = \frac{S_3 S_4 - S_2 S_5}{S_1 S_4 - {S_2}^2} \tag{16}$$

Where:

$$S_1 = \sum_{i=1}^{n} \cos^2\alpha_i$$

$$S_2 = \sum_{i=1}^{n} \sin\alpha_i \cos\alpha_i$$

$$S_3 = \sum_{i=1}^{n} \frac{\cos\alpha_i}{P_i}$$

$$S_4 = \sum_{i=1}^{n} \sin^2\alpha_i$$

$$S_5 = \sum_{i=1}^{n} \frac{\sin\alpha_i}{P_i}$$

Equations 15 and 16 were used to calculate k_1 and k_2 for peak force data (Table 4.3) and for average force data (Table 4.4) data sets. A visual comparison between the two fitted curves and the experimental data is shown in Figures 4.12 and 4.13. Error bars represent one standard deviation.

Table 4.3 – Peak force: Linearized models for conditions A and B.

Condition	Fitting range	k_1	k_2	Minimum at α	
A	0-90°	0.1132	0.1048	47°	
B	0-90°	0.2269	0.2245	45°	Fig. 4.11
A	0-135°	0.1250	0.0941	53°	Fig. 4.10

Table 4.4 – Average force: Linearized models for conditions A and B.

Condition	Fitting range	k_1	k_2	Minimum at α	
A	0-90°	0.2186	0.2017	47°	
B	0-90°	0.2883	0.2781	46°	Fig. 4.11
A	0-135°	0.2508	0.1708	56°	Fig. 4.10

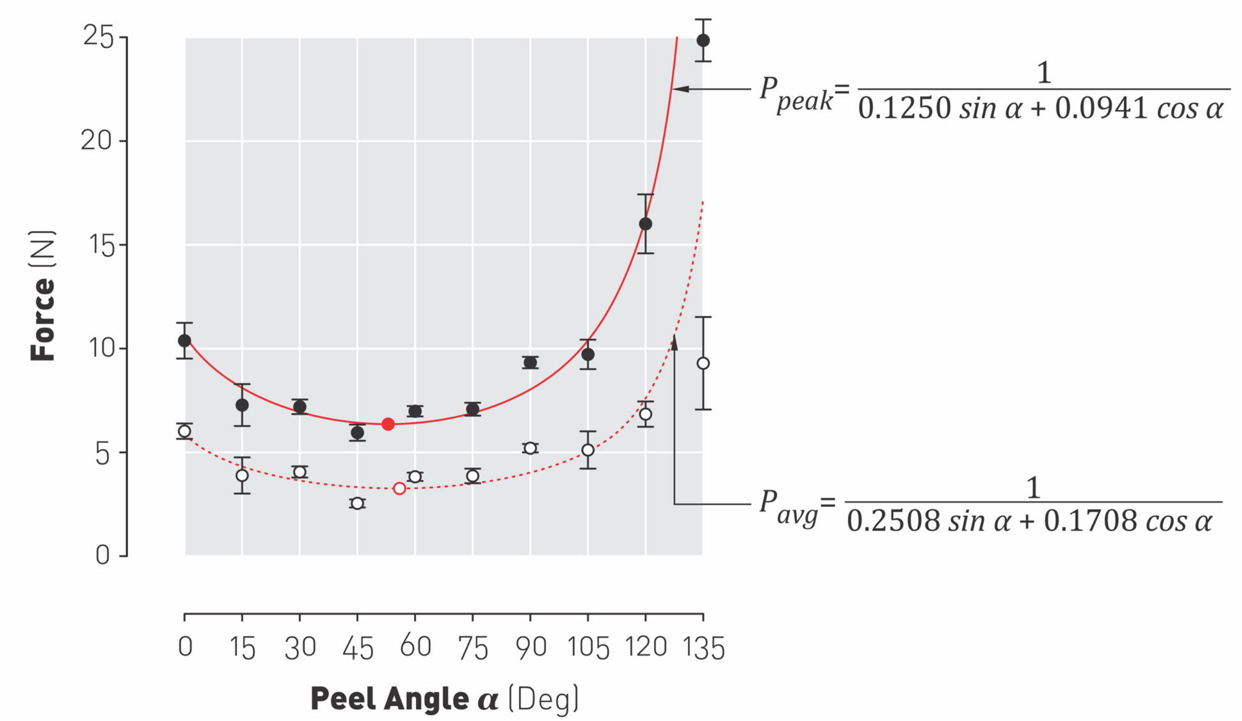

Figure 4.11 – Condition A: Fitted curves over 0-135° range and experimental data for peak (●) and average (○) forces.

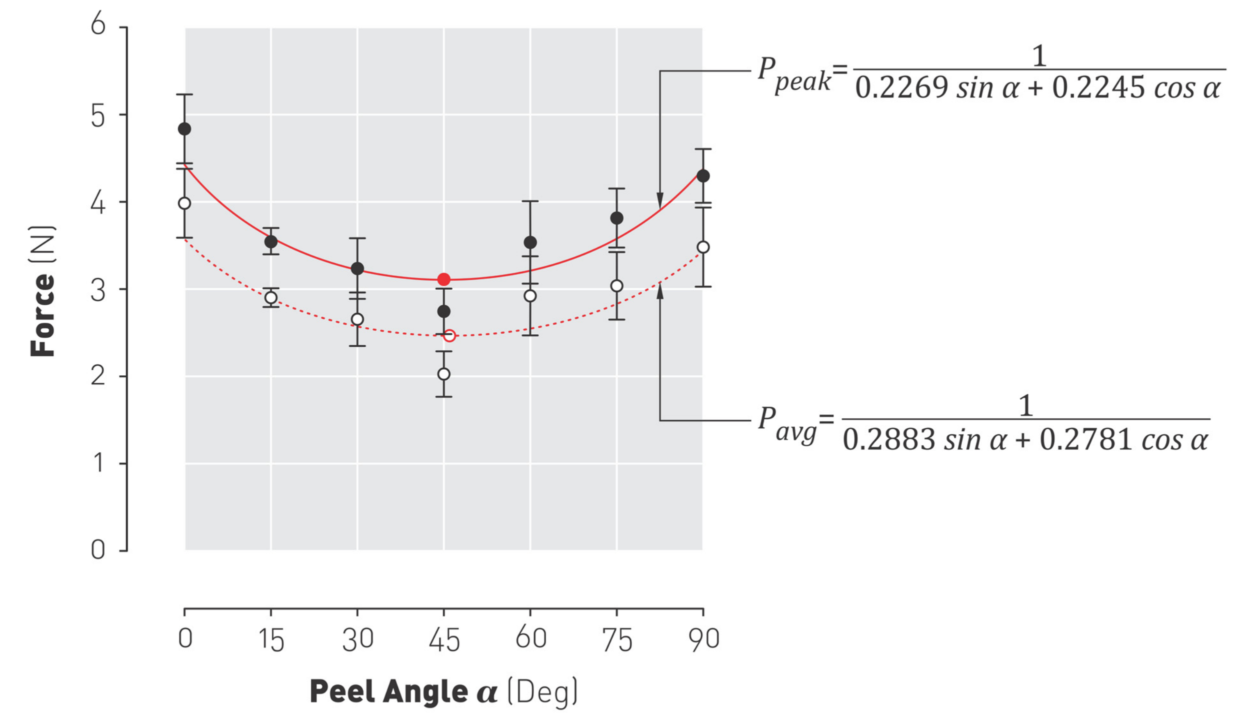

Figure 4.12 – Condition B: Fitted curves over 0-90° range and experimental data for peak (●) and average (○) forces.

4.5.2. Approach 2: Nonlinear Regression

Experimental data were fitted to Equation 6 using nonlinear regression in SigmaPlot™ [12]. The Kolmogorov-Smirnov (*K-S*) test was significant only for average force data coming from condition A in the 0-135 degrees range so normality cannot be assumed (*K-S*=0.1904, p=0.0463). The rest of the *K-S* tests were not significant so it is assumed that data is normally distributed (see Tables 4.5 and 4.6 for *K-S* statistic and significance level values). The three regression models for peak force suggest that between 71% and 91% of the variability of peel force can be explained by angle α (see Table 4.5 for R^2 values for each fitting). Whereas the models for average force indicates that between 62% and 66% of the variation of force is likely to be explained by its relationship with peel angle (see Table 4.6 for R^2 values for each fitting).

Table 4.5 – Peak force: Nonlinear regression results conditions A and B.

Condition	Fitting range	R^2	k_1	k_2	K-S Statistic	Significance level	Minimum at α
A	0-90°	0.7972	0.1121	0.1007	0.1016	0.8436	48°
B	0-90°	0.7069	0.2278	0.2133	0.1497	0.3839	47°
A	0-135°	0.9155	0.1366	0.0824	0.1086	0.5729	59°

Table 4.6 – Average force: Nonlinear regression results conditions A and B.

Condition	Fitting range	R^2	k_1	k_2	K-S Statistic	Significance level	Minimum at α
A	0-90°	0.6630	0.2106	0.1797	0.1343	0.5227	50°
B	0-90°	0.6179	0.2839	0.2603	0.1077	0.7884	47°
A	0-135°	0.6366	0.2838	0.1459	0.1904	0.0463	63°

4.6. Conclusions and discussion

Testing standards such as ASTM F88 and ASTM F2824 acknowledge the effect of peel angle on peel force when peeling packaging seals. However, the literature does not provide mathematical relationships between peel angle and force. This research proposes a simple mathematical relation that shows good agreement with experimental data.

For both conditions, A and B, experimental data followed a U-shaped pattern with minimum force values at peel angles around 45° (Figs. 4.8 and 4.9). Forces increase rapidly beyond peel angles larger than 90°. Kinematics and observational studies conducted by the authors with the same lidded tray suggest that people use peel angles smaller than 90° [13]. For this reason, data for condition A was analyzed and fitted over both peel angles ranges, 0-90° and 0-135°.

The two approaches taken to fit the data, linearization and nonlinear regression, yielded similar parameters. The parameters found for the relationship by linearization yields minimum peak force values at peel angles equal to 45°, 47°, and 53° while minimum average force values were calculated at 46°, 47°, and 56°. Nonlinear regression results yielded minimum peak forces at 47°, 48°, and 59° and minimum average forces at 47°, 50°, and 63°. Minimum force values occur at larger peel angles (53°, 56°, 59°, and 63°) when using a fitting over the 0-135° range. One interpretation is that larger force values occurring beyond 90° likely shift the curve towards the right. When fitting the equation over the 0-90° range, minimum force values occur between 45° and 50°.

Knowing the numerical relation between peel angle and peel force for a given package system has implications for testing standards dealing with packaging peeling. Manufacturers could inform users of the minimum and maximum values for peel forces required to open their semi-rigid packaging based on peel angle and peel line width.

Locating the optimal peel angle has implications for the design of tabs. In order to minimize the force required to peel a tray, a tab should allow pulling the lid at around the optimal peel angle. In addition, from a usability view point, peak force seems a more realistic measure of the ease of opening than average force because it represents the maximum force that a user must apply to peel off the lid. Using the central 80% of the curve to calculate an average force may be adequate for testing a standard 1-inch wide specimen but it may be insufficient to characterize the ease of opening of a whole package. Future steps should include calculating the average force using all data for each tray.

4.7. Limitations

One limitation for this study is that there were many sources of variability:

- The ability of the variable angle test fixture to maintain a constant angle during testing.
- The ability of the sealer to provide uniform seals for all cavities.
- Only one combination of lidstock/tray does not necessarily generalize the relationships found across other materials.

4.8. Acknowledgements

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5

Modeling peel force in peelable semi-rigid packaging

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Abstract

The ability to easily peel the lid of a container is a critical issue for semi-rigid packages used to protect and deliver a myriad of products including medical devices, foods, and beverages. We developed, and present herein, a method to calculate seal strength coefficients for a given semi-rigid packaging system and a mathematical algorithm to calculate peel forces specific to a given system. The advantages of using a mathematical model to predict peel forces are numerous. Predicted force profiles can be used to optimize openability by detecting peak forces, to develop a force profile specific to the container and peel path. We hypothesize that sudden changes in force are likely to result in handling difficulties for some users and are likely related to spills and contamination of sterile contents.

Four regression analyses were applied to assess the model's ability to predict peeling force. Experimental and theoretical values were highly correlated (R=0.789; R=0.764; R=0.709; R=0.717) and the four regression analyses were found significant (p<0.001) with R^2 of 0.622, 0.584, 0.502, and 0.514, suggesting that theoretical values were significant predictors of experimental values. Results show that the proposed mathematical model for peeling semi-rigid packaging can predict experimental values very well. Calculations using average seal strength coefficients seem to predict average and peak forces better than those using peak seal strength coefficients.

Key words

Peelable seal, peeling, packaging design, usability, mathematical model.

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5.1. Introduction

According to the American Society for Testing and Materials (ASTM), a flexible material has a particular combination of flexural strength and thickness that allows a fold at an approximate 180° angle [1]. This definition allows the classification of heat sealed packages into flexible packages and semi-rigid packages based on the flexibility of each of the two substrates of their seal. A flexible package has both sides of the seal made of flexible material such as bags, envelopes, pouches, sachets, wraps, flexible thermoformed films, etc. A semi-rigid package comprises a heat seal in which one side is made of a flexible material and the other is made of rigid. Typical packaging forms with these characteristics encompass trays, bowls, cups, pots, and even induction seals on bottle finishes.

The ability to easily peel the lid of a container is a critical issue for semi-rigid packages. This includes any heat or induction sealed package typically used for protecting and delivering medical devices, food, and beverages. A typical peelable seal includes a tab, attached to the lid, which is used to enable people to overcome sealing forces. The tab becomes a tool to exert a pulling force sufficient to separate the lid stock from the tray.

Research studies on the topic of peelable seals for packaging have focused on optimizing the heat sealing process [2-4], describing the mechanics of peeling [5], and describing testing procedures to measure opening forces and peel concepts [6]. A vast body of research has focused on reporting issues related to tab design, most studies have focused on two issues: noticeability and effectiveness.

The noticeability of a tab is related to perceptual and cognitive processes during human-package interactions. Perceptual problems occur when the opening mechanism is not clearly apparent (either by touch or sight) on the package. A cognitive problem occurs when the opening feature is incomprehensible or not perceived as intended. Several survey and focus group studies have reported that finding a tab on a package is a frequent challenge [7-10].

The second issue, the effectiveness of a tab, is related to motor or physical problems. Problems occur when the user does not have the necessary physical ability (i.e., strength, dexterity, range of motion) to open/handle a package. In the case of tabs, fine dexterity is needed to produce the initial grip; force and motion are needed to hold the package and remove the lid. Studies using surveys [9-12], focus groups [7, 11], and package testing [13, 14] have described these issues for healthy adults, older adults, and people with disabilities. In addition, a number of studies have measured user's pull tear strength with custom-built devices designed to mimic the type of force needed in tab opening [12, 15-19].

The work presented herein is part of a project that intends to correlate how the design of peelable seals and tabs impact forces, movement, and, ultimately, package functionality during the opening process. Modeling the relationship between design variables and force will enable the optimization of peelable seals, minimizing costs associated with tooling and materials while maximizing user ability. Our literature review revealed a lack of mathematical tools that allow the prediction and simulation of forces during peeling of lidded trays.

5.2. Objectives

The objectives of this study are:

1) To develop a method to determine seal strength coefficients for a given semi-rigid packaging system.
2) To develop a set of equations for determining position, direction, and magnitude of peel forces when peeling a lid in a semi-rigid packaging system.
3) To validate the mathematical model by comparing its prediction against empirical data.

5.3. Materials and methods

5.3.1. Theoretical model

Consider the system depicted in Figure 5.1, a semi-rigid packaging system consisting of a tray and a lid.

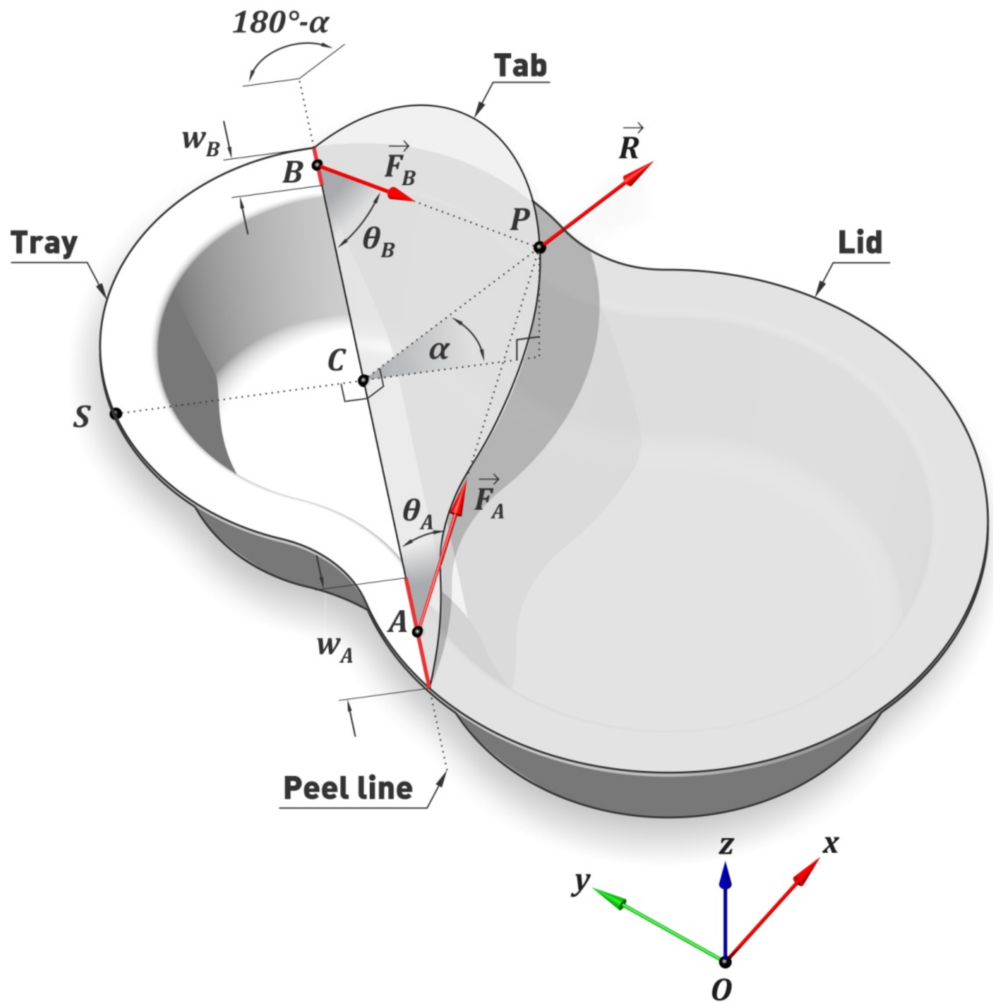

Figure 5.1 – System of forces in a semi-rigid packaging system.

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Peeling starts at point S, which can be any point on the perimeter of the seal area. The tab is pulled to start the peeling of the lid. The peel line, a perpendicular line to the peeling direction, is defined as an imaginary line passing trough points A and B, both located in the center of the seal area. The plane of the tab makes an angle α with the unpeeled portion of the lid. The start point S moves to end point P via a rotation through an angle of 180°-α about an axis represented by the peel line. The first step is finding the coordinates of P, where the peel force $\vec{R}$ is applied:

Coordinates of P

Definitions:

$\overline{OP} = P = (x_P, y_P, z_P) \ = x_P\hat{\imath} + y_P\hat{\jmath} + z_P\hat{k}$ coordinates of P

$\overline{OS} = S = (x_S, y_S, 0) = x_S\hat{\imath} + y_S\hat{\jmath}$ coordinates of S

$A = (x_A, y_A, 0) = x_A\hat{\imath} + y_A\hat{\jmath}$ coordinates of A

$B = (x_B, y_B, 0) = x_B\hat{\imath} + y_B\hat{\jmath}$ coordinates of B

Equations:

Sum of vectors:

$$\overline{OP} = \overline{OS} + \overline{SC} + \overline{CP} = \overline{OS} - \overline{CS} + \overline{CP} \tag{1}$$

$$\overline{CP} = -\overline{CS}\, cos\, \alpha + \left|\overline{CP}\right| sin\, \alpha\, \hat{k} \tag{2}$$

Substituting (2) in (1):

$$\overline{OP} = \overline{OS} - \overline{CS}(1 + cos\, \alpha) + \left|\overline{CP}\right| sin\, \alpha\, \hat{k} \tag{3}$$

$$\left|\overline{CP}\right| = \widehat{AB} \times \overline{AS} \cdot \hat{k} \tag{4}$$

$$\overline{AC} = \left(\widehat{AB} \cdot \overline{AS}\right)\widehat{AB} \tag{5}$$

$$\overline{CS} = \overline{AS} - \overline{AC} = \overline{AS} - \left(\widehat{AB} \cdot \overline{AS}\right)\widehat{AB} \tag{6}$$

Substituting (6) and (4) in (3):

$$\overline{OP} = \overline{OS} - \left[\overline{AS} - \left(\widehat{AB} \cdot \overline{AS}\right)\widehat{AB}\right](1 + cos\, \alpha) + \left[\widehat{AB} \times \overline{AS} \cdot \hat{k}\right] sin\, \alpha\, \hat{k} \tag{7}$$

$$\overline{AS} = (x_S - x_A)\hat{\imath} + (y_S - y_A)\hat{\jmath} \tag{8}$$

$$\widehat{AB} = \frac{(x_B - x_A)\hat{\imath} + (y_B - y_A)\hat{\jmath}}{\sqrt{(x_B - x_A)^2 + (y_B - y_A)^2}} \tag{9}$$

$$\widehat{AB} \cdot \overline{AS} = \frac{(x_S - x_A)(x_B - x_A) + (y_S - y_A)(y_B - y_A)}{\sqrt{(x_B - x_A)^2 + (y_B - y_A)^2}} \tag{10}$$

$$\widehat{AB} \times \overline{AS} \cdot \hat{k} = \frac{1}{\sqrt{(x_B - x_A)^2 + (y_B - y_A)^2}} \begin{vmatrix} 0 & 0 & 1 \\ x_B - x_A & y_B - y_A & 0 \\ x_S - x_A & y_S - y_A & 0 \end{vmatrix} \tag{11}$$

$$= \frac{(x_B - x_A)(y_S - y_A) - (x_S - x_A)(y_B - y_A)}{\sqrt{(x_B - x_A)^2 + (y_B - y_A)^2}} \tag{12}$$

$$\begin{aligned} &\overline{OP} \\ &\quad = x_S\hat{\imath} + y_S\hat{\jmath} - (1 \\ &\quad + \cos\alpha)\Bigg[(x_S - x_A)\hat{\imath} + (y_S - y_A)\hat{\jmath} \\ &\quad - \frac{(x_S - x_A)(x_B - x_A) + (y_S - y_A)(y_B - y_A)}{\sqrt{(x_B - x_A)^2 + (y_B - y_A)^2}} \cdot \frac{(x_B - x_A)\hat{\imath} + (y_B - y_A)\hat{\jmath}}{\sqrt{(x_B - x_A)^2 + (y_B - y_A)^2}}\Bigg] \\ &\quad + \sin\alpha\left[\frac{(x_B - x_A)(y_S - y_A) - (x_S - x_A)(y_B - y_A)}{\sqrt{(x_B - x_A)^2 + (y_B - y_A)^2}}\right]\hat{k} \end{aligned} \tag{13}$$

$$\begin{aligned} &x_P \\ &\quad = x_S - (1 \\ &\quad + \cos\alpha)\left[x_S - x_A - \frac{(x_S - x_A)(x_B - x_A) + (y_S - y_A)(y_B - y_A)}{(x_B - x_A)^2 + (y_B - y_A)^2}(x_B - x_A)\right] \end{aligned} \tag{14}$$

$$\begin{aligned} &y_P \\ &\quad = y_S - (1 \\ &\quad + \cos\alpha)\left[y_S - y_A - \frac{(x_S - x_A)(x_B - x_A) + (y_S - y_A)(y_B - y_A)}{(x_B - x_A)^2 + (y_B - y_A)^2}(y_B - y_A)\right] \end{aligned} \tag{15}$$

$$z_P = \sin\alpha\left[\frac{(x_B - x_A)(y_S - y_A) - (x_S - x_A)(y_B - y_A)}{\sqrt{(x_B - x_A)^2 + (y_B - y_A)^2}}\right] \tag{16}$$

Forces $\vec{F}_A$, $\vec{F}_B$, and $\vec{R}$

Definitions:

$\vec{\boldsymbol{R}}$ Resultant peel force applied at P

$\vec{\boldsymbol{F}}_{\boldsymbol{A}}$ Peel force applied at A

$\vec{\boldsymbol{F}}_{\boldsymbol{B}}$ Peel force applied at B

$\boldsymbol{w}_{\boldsymbol{A}}$ Peel line width at A

$\boldsymbol{w}_{\boldsymbol{B}}$ Peel line width at B

$\boldsymbol{\theta}_{\boldsymbol{A}}$ Angle between direction of $\vec{F}_A$ and rotation axis $\overline{AB}$

$\boldsymbol{\theta}_{\boldsymbol{B}}$ Angle between direction of $\vec{F}_B$ and rotation axis $\overline{AB}$

$\boldsymbol{S}_{\boldsymbol{\alpha}}$ Seal strength, force per unit of length at a given peel angle α

The equations of equilibrium of the peeled portion of the lid are:

$$F_A \sin\theta_A = S_\alpha w_A \rightarrow F_A = \frac{S_\alpha w_A}{\sin\theta_A} \tag{17}$$

$$F_B \sin\theta_B = S_\alpha w_B \rightarrow F_B = \frac{S_\alpha w_B}{\sin\theta_B} \tag{18}$$

$$\vec{R} = \vec{F}_A + \vec{F}_B = F_A\widehat{AP} + F_B\widehat{BP} \tag{19}$$

$$\vec{R} = \frac{S_\alpha w_A}{\sin\theta_A} \cdot \frac{(x_P - x_A)\hat{\imath} + (y_P - y_A)\hat{\jmath} + z_P\hat{k}}{\sqrt{(x_P - x_A)^2 + (y_P - y_A)^2 + {z_P}^2}} + \frac{S_\alpha w_B}{\sin\theta_B} \cdot \frac{(x_P - x_B)\hat{\imath} + (y_P - y_B)\hat{\jmath} + z_P\hat{k}}{\sqrt{(x_P - x_B)^2 + (y_P - y_B)^2 + {z_P}^2}} \tag{20}$$

Angles θ_A and θ_B

Equations:

$$cos\,\theta_A = \widehat{AB} \cdot \widehat{AP} \rightarrow \theta_A = cos^{-1}\left(\widehat{AB} \cdot \widehat{AP}\right) \tag{21}$$

$$cos\,\theta_B = -\widehat{AB} \cdot \widehat{BP} \rightarrow \theta_B = cos^{-1}\left(-\widehat{AB} \cdot \widehat{BP}\right) \tag{22}$$

$$\theta_A = cos^{-1}\left[\frac{(x_B - x_A)(x_P - x_A) + (y_B - y_A)(y_P - y_A)}{\sqrt{(x_B - x_A)^2 + (y_B - y_A)^2}\sqrt{(x_P - x_A)^2 + (y_P - y_A)^2 + {z_P}^2}}\right] \tag{23}$$

$$\theta_B = cos^{-1}\left[-\frac{(x_B - x_A)(x_P - x_B) + (y_B - y_A)(y_P - y_B)}{\sqrt{(x_B - x_A)^2 + (y_B - y_A)^2}\sqrt{(x_P - x_A)^2 + (y_P - y_A)^2 + {z_P}^2}}\right] \tag{24}$$

5.3.2. Experiment 1: Seal strength measurement

5.3.2.1 Procedure

The peak force and average force needed to completely peel off two rectangular sealed areas of a flexible lid bonded to a tray were measured using a universal tensile testing machine (Instron Inc., Norwood, MA) for seven values of α (0, 15, 30, 45, 60, 75, and 90 degrees) at a rate of 12 in/min (300 mm/min). Peak force is defined as the highest force across the 100% of the data. Average force was calculated using data only from the central 80% of the curve as ASTM F88 suggests [1]. Five replicates of each of the seven conditions were recorded. Each sealed tray was secured to a variable angle test fixture at specific position of α. The length of the rectangular sealed areas was 76 mm (Fig. 5.2). Peel line widths were measured after tensile testing using a Bridgeport optical comparator equipped with a Quadra Chek 2000 digital readout (Heidenhain Inc., Schaumburg, IL). Average peel line width ($\overline{w}$) was calculated as the average of the initial and final width values of each of the two rectangular sealed areas (Eq. 25). Seal strength coefficients, defined as force per unit of length, for peak and average forces were calculated using the average peel line width (Eqs. 26 and 27).

$$\bar{w} = \bar{w}_1 + \bar{w}_2 = \frac{w_{1i} + w_{1f}}{2} + \frac{w_{2i} + w_{2f}}{2} \tag{25}$$

$$s_{peak} = \frac{R_{peak}}{\bar{w}} \tag{26}$$

$$s_{avg} = \frac{R_{avg}}{\bar{w}} \tag{27}$$

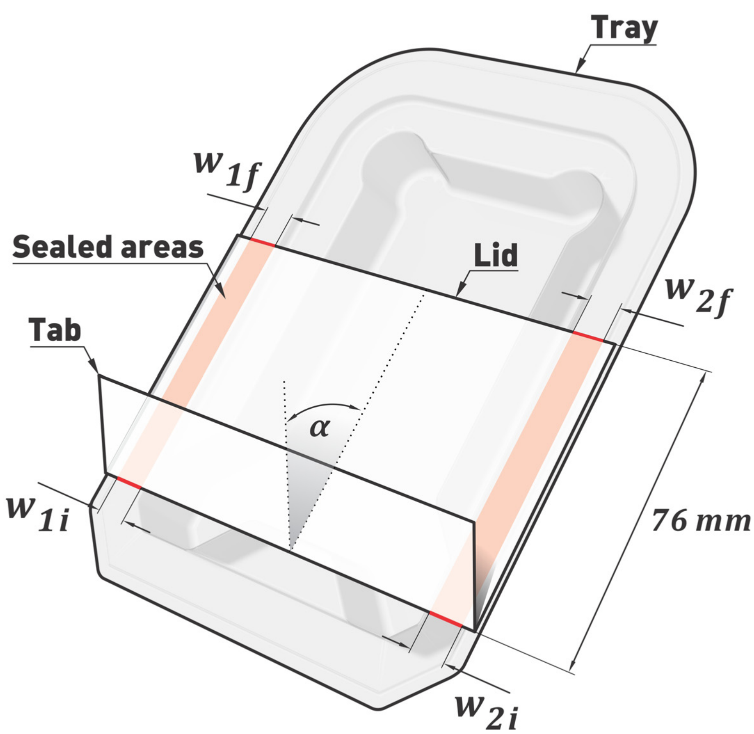

Figure 5.2 – Rectangular sealed areas (in red) of a tray inclined at α=45°.

5.3.2.2. Packages

Trays were thermoformed from a blue tint uncoated PETG, preform thickness of 0.025 inches using the mold "Medtronic Inc. outer tray part number 350215-001" (Perfecseal ,Oshkosh, WI). Trays were sealed with PTH-017 seal coated 1073B Tyvek® die cut lids

(Amcor Flexibles Healthcare, Madison, WI) using a CeraTek MD-2420 shuttle-style heat sealer (SencorpWhite, Hyannis, MA). In order to temporarily fix the trays to the fixture, each had a 3/16 in hole drilled in the center of its bottom. Through this hole it was affixed to a rectangular piece of plywood (thickness ¼ in × width 2 in × length 3.5 in) that held the bottom of the tray flat against the fixture using a round machine screw (size 10-24 × length ¾ in) prior to sealing. After being sealed, part of the lid was removed leaving a 25 mm tab and 76 mm of straight seal intact (Fig. 5.2).

5.3.2.3. Heat sealing

The heat sealer temperature was 150°C, the pressure was 70 psi, and the cycle time 3 seconds. After sealing, trays were visually inspected for defects according to ASTM F1886 Standard Test Method for Determining Integrity of Seals for Medical Packaging by Visual Inspection [20]. Trays with visible defects were removed. Each tray was identified by a code made up of a sealing position (from A, top left cavity, throughout I, bottom right cavity) and run number.

5.3.2.4. Variable angle test fixture

The variable angle test fixture was designed and built so that it holds the tray such that angles α and β are maintained throughout testing. The fixture consists of a ramp attached to a cart with wheels that kept the sample vertical while peeling. A protractor allows the platform to be fixed at seven positions with 15-degrees intervals, from 0 through 90 degrees. The tray is bolted to the platform, and a special gripping device grips the tray tab with upper jaw of the tensile testing machine. As the crosshead moves vertically, the cart moves along a rail, maintaining a constant angle during peeling

5.3.2.5. Experiment 1: Results

Peak force, average force, average peel line width, and seal strength coefficients for seven values of α are shown in Table 5.1. On average, average seal strength coefficients ($\boldsymbol{s_{avg}}$) were 19% lower (range=18-26%) than the peak seal strength coefficients (s_{peak}) (Fig. 5.3 and Table 5.1). The average total peel line width was 18.56 mm (*sd*=0.31 mm).

Table 5.1 – Summary of forces, peel line widths, and seal strength.

α	R_{peak}	R_{avg}	$\overline{w}$	s_{peak}	s_{avg}	$\frac{s_{peak} - s_{avg}}{s_{peak}}$
Peel Angle	**Peak Force**	**Average Force**	**Total Peel Line Width**	**Peak Seal Strength**	**Average Seal Strength**	**Percent Difference**
(Deg)	(N)	(N)	(mm)	(N/mm)	(N/mm)	(%)
0	4.88 ±0.33	4.03±0.38	18.4 ±0.34	0.26 ± 0.02	0.22 ± 0.02	17
15	3.58 ±0.21	2.94±0.10	18.74±0.37	0.19 ± 0.01	0.16 ± 0.01	18
30	3.27 ±0.25	2.68±0.31	18.60±0.37	0.18 ± 0.02	0.14 ± 0.02	18
45	2.78 ±0.25	2.06±0.26	18.52±0.29	0.15 ± 0.01	0.11 ± 0.01	26
60	3.57 ±0.22	2.96±0.44	18.70±0.22	0.19 ± 0.03	0.16 ± 0.02	17
75	3.85 ±0.25	3.08±0.38	18.35±0.35	0.21 ± 0.02	0.17 ± 0.02	20
90	4.33 ±0.40	3.52±0.44	18.61±0.20	0.23 ± 0.02	0.19 ± 0.02	19

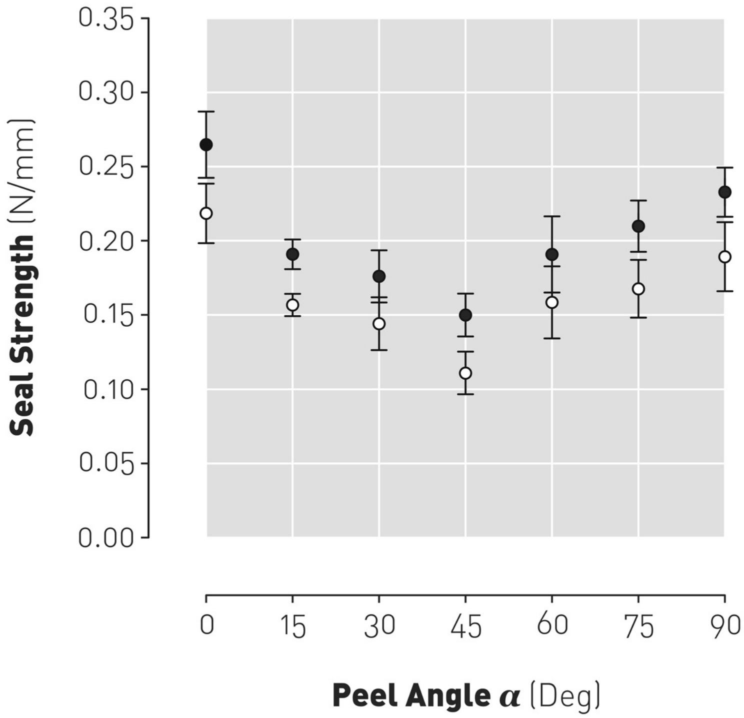

Figure 5.3 – Peak (●) and average (○) seal strength vs. peel angle.

5.3.3. Experiment 2: Theoretical peel force calculation and comparison with experimental values

5.3.3.1. Procedure

The mathematical model described at the beginning of the Materials and Methods section and the seal strength coefficients from Experiment 1 were used in an algorithm to calculate the theoretical peel force needed to peel off different seal area shapes. The algorithm was programmed in MATLAB® [21]. The process included the following steps:

1) Seal area dimensioning: the land area of the seal was dimensioned using the tray's manufacturing drawings and assuming a constant seal width of 9.28 mm, half the average total peel line width obtained from Experiment 1 (i.e., 18.56 mm).

2) Geometry division: the dimensioned drawing was divided into discrete segments of equal lengths of 1 mm.
3) Data importing: all segments' coordinates were exported in an .XLS file format and then imported from the MATLAB® program.
4) Peel angle definition (α): a specific peel angle is chosen so the seal strength coefficient (S) can be defined.
5) Peel line width calculation (w_A and w_B): the imported data is used to calculate the peel line widths by intersecting a line perpendicular to the peel direction with the sealed areas.
6) Peel force calculation (R): for each total peel line width value a resultant peel force is calculated using the equations described before.
7) Steps 5 and 6 are repeated until the entire, theoretical seal is "peeled off". On each iteration, the intersecting line is moved an incremental value (i.e., 0.1 mm) along the peel line direction.

The perimeters of the sealed area were measured from the peeled trays, drawn, and divided in segments of equal distance (i.e., 1 mm) using Rhinoceros® [22], a computer aided design software for 3D modeling. Two-dimensional coordinates were then exported to Excel® format using the "ExportPointsToExcel" script. Thus, the seal perimeter was transformed into a succession of nodes. The MATLAB® program loads the data into memory and simulates a peeling of the sealed area at specified peel angle and direction.

A virtual geometry that consisted of the entire tray's seal area with a constant width of 9.28 mm was created to calculate peeling forces. Figure 5.4 shows an intermediate state where peeling has already been started. Two types of theoretical peeling forces were calculated for each peel angle and for each seal strength coefficients (average and peak):

- Average Force (R_{avg}): force is averaged using the central 80% portion of the peeling simulation.
- Peak Force (R_{peak}): the highest force across the 100% of the peeling simulation.

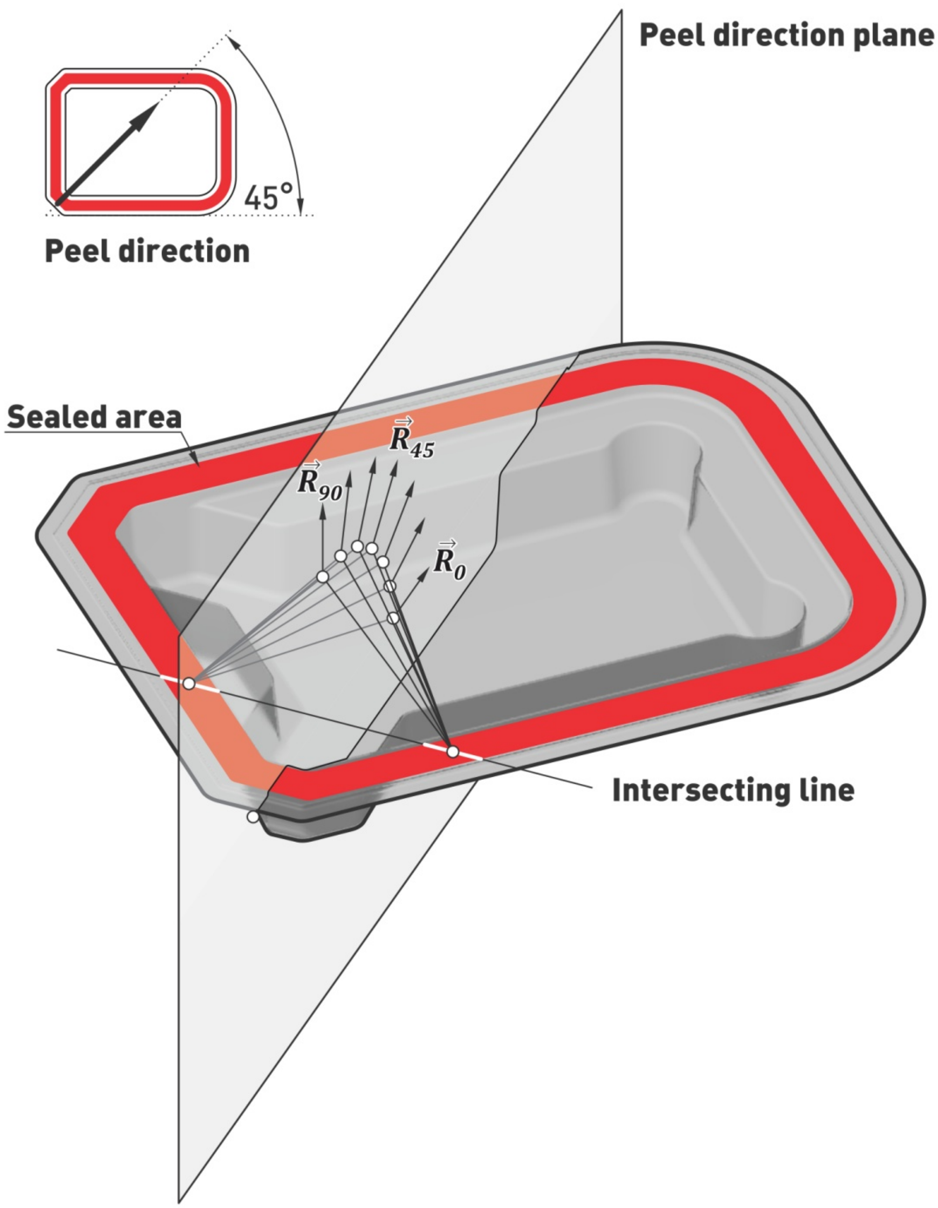

Figure 5.4 – Sealed area with constant width and peel direction at 45° with respect to the longer tray's edge.

5.3.3.2. Experiment 2: Results

Figure 5.5 shows a typical plot for a specific peeling angle (α=60°) combining five experimental replicates and theoretical calculations using the algorithm.

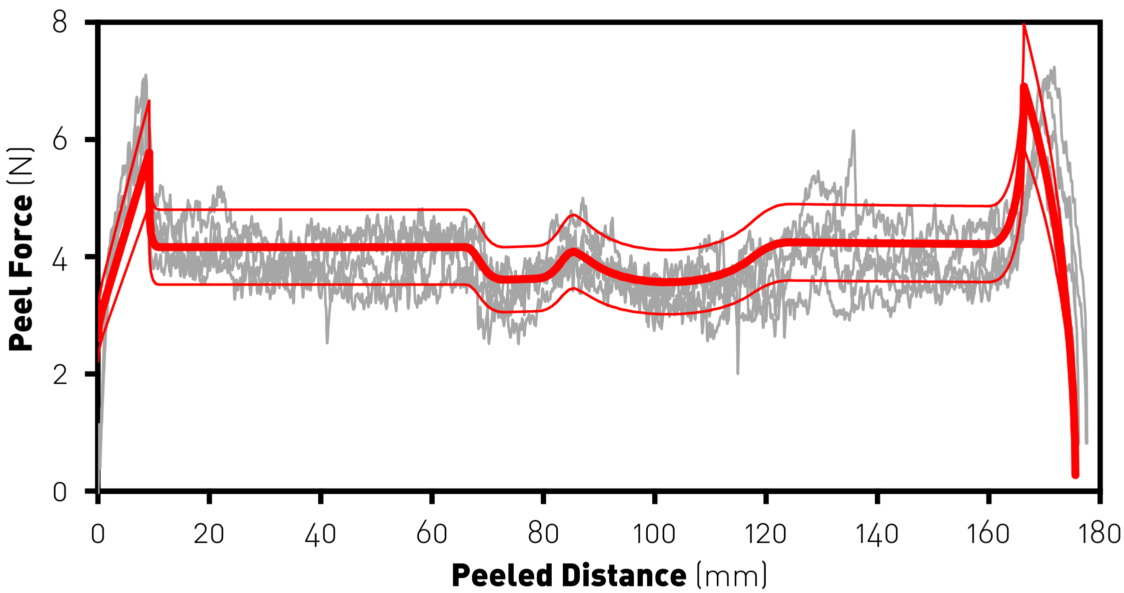

Figure 5.5 – Typical Peel Force vs. Peeled Distance plot for a sample peeled at α=60°. Comparison between five experimental measurements (in gray) and theoretical force (in red) calculated using the average seal strength coefficient for α=60°. The upper and lower red lines represent one standard deviation from the mean.

Regression analysis was applied to assess model's ability to predict the peeling force using PROC REG in SAS 9.2 [23]. Experimental and theoretical values were highly correlated and the four regression analyses were found significant (α=0.05). Table 5.2 summarizes the regression results. Further assessment of models was done by analysis of variance using PROC MIXED procedure. Means within each angle of both methods were compared using Fisher's LSD pairwise comparisons (α=0.05). In addition, percent differences between and t-test comparisons values were performed for each peel angle.

Table 5.2 – Regression analysis results comparing theoretical and experimental values.

Seal Strength	Force	R	R^2	F	p-value
s_{avg}	Average	0.789	0.622	31.284	< 0.0001
	Peak	0.764	0.584	26.688	< 0.0001
s_{peak}	Average	0.709	0.502	19.159	< 0.0001
	Peak	0.717	0.514	20.090	< 0.0001

5.3.3.2.1 Average force prediction

Theoretical average force values calculated using average seal strength (s_{avg}) and average force experimental measurements were highly correlated (R=0.789). The regression analysis for this comparison was significant (p<0.001) with an R^2 of 0.622 suggesting that these theoretical values are significant predictors of average force experimental values. Theoretical average force values calculated using peak seal strength (s_{peak}) and average force experimental measurements were also highly correlated (R=0.764). The regression analysis for this comparison was significant (p<0.001) with an R^2 of 0.584. A comparison between the two data sets is shown in Table 5.3 and Figure 5.6. The seven t-test comparisons were not significant. The average percent difference across the seven peeling angles was 8% (*min*=2%, *max*=12%). Predicted values for Average Force using peak seal strength coefficients (s_{peak}) were good for angles from 0, 15, and 30 degrees but overestimated experimental values for peel angles between 45 through 90 degrees (Table 5.3 and Fig. 5.7).

Table 5.3 – Experimental and theoretical comparison for Average Force (R_{avg}). Theoretical values calculated using average seal strength (s_{avg}).

α Peel Angle (Deg)	R_E Experimental Average Force (N)	R_T Theoretical Average Force (N)	p *t* Test one-tail p-value	$\frac{\lvert R_T - R_E \rvert}{R_T}$ Percent Difference (%)
0	6.05 ± 0.37	5.54 ± 0.51	0.11	9
15	3.91 ± 0.84	3.98 ± 0.19	0.44	2
30	4.09 ± 0.21	3.66 ± 0.45	0.13	12
45	2.54 ± 0.19	2.82 ± 0.36	0.16	10
60	3.82 ± 0.20	4.02 ± 0.62	0.25	5
75	3.86 ± 0.35	4.25 ± 0.49	0.16	9
90	5.23 ± 0.20	4.80 ± 0.59	0.09	9

* None of the differences were statistically significant at p=0.05

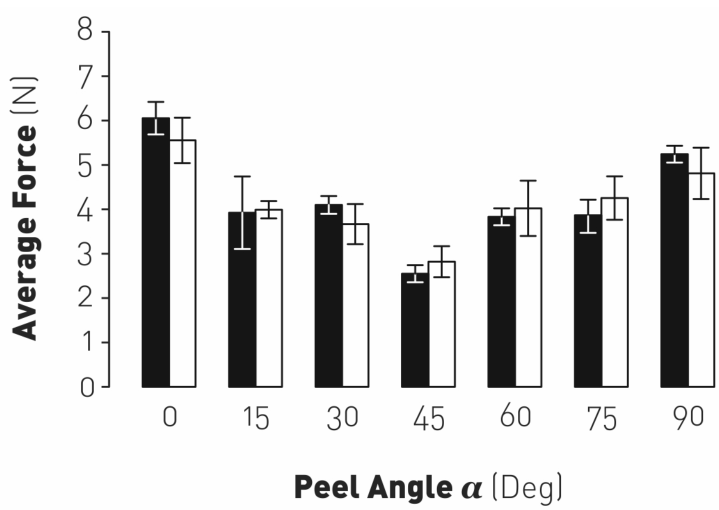

Figure 5.6 – Comparison of experimental and theoretical average forces at various peel angles. Experimental (■); Theoretical values calculated using average seal strength (□).

Table 5.4 – Experimental and theoretical comparison for Average Force (R_{avg}). Theoretical values calculated using peak seal strength (s_{peak}).

α **Peel Angle** (Deg)	R_E **Experimental Average Force** (N)	R_T **Theoretical Average Force** (N)	p ***t* Test one-tail p-value**	$\frac{\lvert R_T - R_E \rvert}{R_T}$ **Percent Difference** (%)
0	6.05 ± 0.37	6.72 ± 0.57	0.082	9
15	4.57 ± 0.41	4.84 ± 0.25	0.177	2
30	4.26 ± 0.75	4.47 ± 0.45	0.345	12
45	2.54 ± 0.19	3.80 ± 0.37	0.006*	10
60	3.82 ± 0.20	4.84 ± 0.65	0.007*	5
75	3.86 ± 0.35	5.32 ± 0.44	0.004*	9
90	5.23 ± 0.20	5.91 ± 0.42	0.040*	9

* Difference is statistically significant at p=0.05

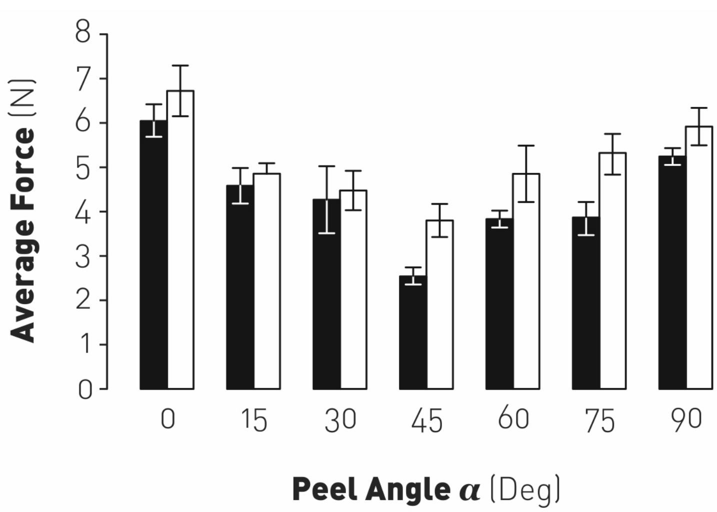

Figure 5.7 – Comparison of experimental and theoretical average forces at various peel angles. Experimental (■); Theoretical values calculated using peak seal strength (□).

5.3.3.2.2. Peak force prediction

Theoretical peak force values calculated using average seal strength (s_{avg}) and peak force experimental measurements were highly correlated (R=0.764). The regression analysis for this comparison was significant (p<0.001) with an R^2 of 0.584 suggesting that these theoretical values are significant predictors of peak force experimental values. Theoretical peak force values calculated using peak seal strength (s_{peak}) and peak force experimental measurements were also highly correlated (R=0.717). The regression analysis for this comparison was significant (p<0.001) with an R^2 of 0.514.

A comparison between them is shown in Table 5.4 and Figure 5.8. Five of the t-test comparisons were not significant and two were significant (for α=45° p=0.03, and for α=90° p=0.02). The average percent difference across the seven peeling angles was 10% (min=1%, max=23%). Predicted values for peak force using peak seal strength coefficients (s_{peak}) were good for angles 0 through 45 degrees but overestimated experimental values for peel angles between 60, 30, and 90 degrees (Table 5.5 and Fig. 5.9).

Table 5.5 – Experimental and theoretical comparison for Peak Force (R_{peak}). Theoretical values calculated using average seal strength (s_{avg}).

α **Peel Angle** (Deg)	R_E **Experimental Peak Force** (N)	R_T **Theoretical Peak Force** (N)	p ***t* Test one-tail p-value**	$\frac{\lvert R_T - R_E \rvert}{R_T}$ **Percent Difference** (%)
0	10.43 ± 0.86	9.52 ± 0.88	0.11	10
15	7.32 ± 1.00	6.83 ± 0.33	0.23	7
30	7.22 ± 0.35	6.28 ± 0.78	0.07	15
45	5.95 ± 0.39	4.84 ± 0.62	0.03*	23
60	6.98 ± 0.25	6.90 ± 1.06	0.44	1
75	7.08 ± 0.31	7.30 ± 0.85	0.30	3
90	9.39 ± 0.23	8.25 ± 1.02	0.02*	14

* Difference is statistically significant at p=0.05

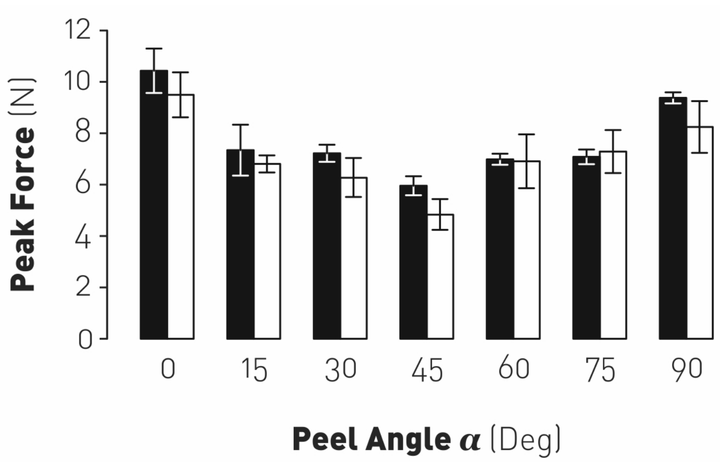

Figure 5.8 – Comparison of experimental and theoretical peak forces at various peel angles. Experimental (■); Theoretical values calculated using average seal strength (□).

Table 5.6 – Experimental and theoretical comparison for Peak Force (R_{peak}). Theoretical values calculated using average seal strength (s_{peak}).

α	R_E	R_T	p	$\frac{\lvert R_T - R_E \rvert}{R_T}$
Peel Angle	**Experimental Peak Force**	**Theoretical Peak Force**	***t* Test one-tail p-value**	**Percent Difference**
(Deg)	(N)	(N)		(%)
0	10.43 ± 0.86	10.57 ± 0.97	0.09	10
15	7.32 ± 1.00	7.88 ± 0.44	0.19	12
30	7.22 ± 0.35	6.90 ± 0.77	0.49	0
45	5.95 ± 0.39	5.90 ± 0.63	0.12	9
60	6.98 ± 0.25	7.20 ± 1.12	0.02*	16
75	7.08 ± 0.31	8.39 ± 0.75	0.02*	23
90	9.39 ± 0.23	9.42 ± 0.72	0.03*	7

* Difference is statistically significant at p=0.05

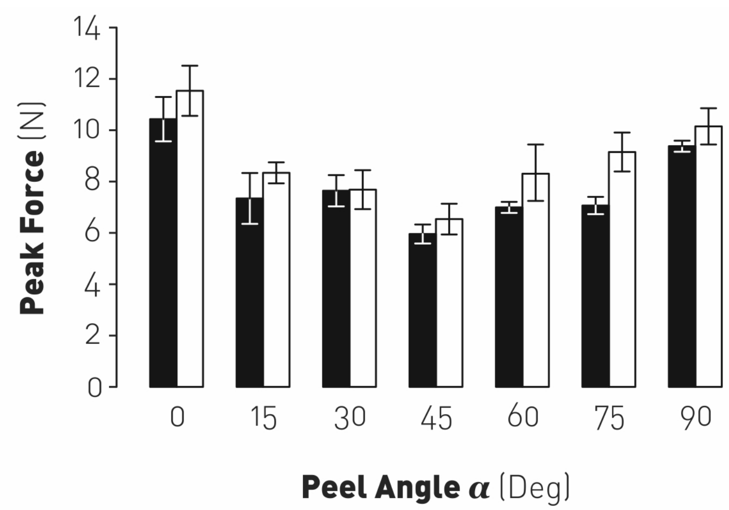

Figure 5.9 – Comparison of experimental and theoretical peak forces at various peel angles. Experimental (■); Theoretical values calculated using peak seal strength (□).

5.4. Conclusions and discussion

This paper describes a method to calculate seal strength coefficients for a given semi-rigid packaging system and proposes mathematical model and algorithm to predict experimental peeling forces based on those coefficients.

Results show that the proposed mathematical model for peeling semi-rigid packaging can predict experimental values very well. Calculations using average seal strength coefficients seem to predict average and peak forces better than those using peak seal strength coefficients.

The advantages of using a mathematical model to predict peel forces are numerous. First, simulations using different container/seal geometries reduce time and prototyping costs. Second, simulated force profiles can be used to optimize openability by detecting peak forces beyond usability criteria and by providing a measure of force variability during opening. Sudden force changes might be difficult to handle for some users and cause usability problems such as accidental spills and contamination of sterile contents. Items that must be presented in sterile form (e.g., medical devices) and liquid products have particular potential to benefit. The creation of designs that induce a uniform force, or those that smooth the rate of change of force, will induce smoother openings, minimizing the problems that can occur from large differences in force during the opening process.

5.5. Limitations

One limitation for this study is that there were many sources of variability:

- The ability of the variable angle test fixture to maintain a constant angle during testing.
- The ability of the sealer to provide uniform seals for all cavities.

5.6. Acknowledgements

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REFERENCES

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6

Peel direction during opening task

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Abstract

Previous studies by the authors have suggested the existence of a range of optimal peel angles ($\alpha \approx 45$) where peeling force is minimized. It is also known that peeling force is proportional to the width of the peeling line. We assume that there should exist for every semi-rigid package, a theoretical optimal path that follow the midpoints of the shortest peel lines. Moreover, we hypothesize people will adjust peeling direction by trying to peel on the optimal path (defined by β) at an optimal peel angle (defined by α).

A motion capture system was used to measure peel angles (α) and peel direction angles (β) during an opening task under two experimental setups (i.e., unrestrained and restrained). Sixteen participants opened lidded trays with retro-reflective markers attached to the lids and trays. Peel angle was measured by using two approaches: α_I or initial peel angle (an average of the first half second of the pulling phase data) and α_T or

total peel angle (an average of the entire pulling phase data). Peel direction angle (β_I) was calculated by averaging the first half second of the pulling phase data.

Mean peel angle (α) measurements (43°, 44°, 44°, and 49°) fell in the optimal peel angle range ($\alpha \approx 45°$) in which pulling force is minimized. For the restrained opening condition, between 62-75% of all participants used peel angles within optimal range. For the unrestrained opening condition, between 69-81% of all participants used peel angles within optimal range.

The initial peel direction angle (β_I) measured during the unrestrained opening condition (β_I=48°, *sd*=22°) approximated the theoretical angle of β=45° confirming that most participants pulled the tab in this direction during the initial stages of the opening task. The initial peel direction angle β_I measured with the restrained opening condition (β_I=34°, *sd*=13°) was significantly lower but still in the range if standard deviation is considered.

On average, most participants used peel angles and peel direction angles close to the hypothesized values ($\alpha \approx 45$ and $\beta \approx 45°$). Experimental setup had an effect on opening time and peel direction angle but did not have a significant effect on peel angle.

Key words

Peelable seal, peeling, packaging design, usability, kinematics, biomechanics, user optimization

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6.1. Introduction

Peel direction has been defined in previous work as comprising two angles: α and β (Fig. 6.1) [1]. Angle α or "peel angle" is the inclination of a tab with respect to the seal plane and angle β or the 'peel direction angle" is the angle that the force vector $\vec{P}$ forms with the longest tray's edge (in a rectangular tray).

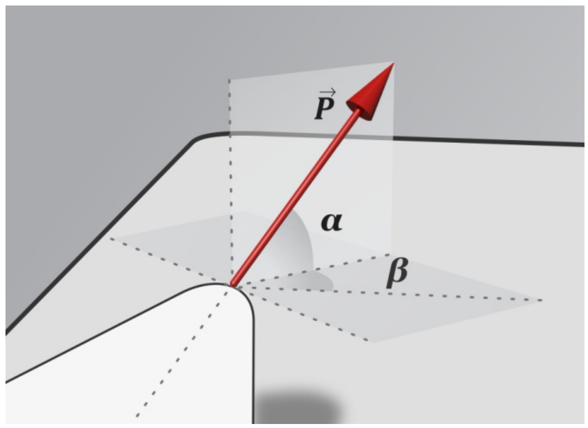

Figure 6.1 – Peel angle α and peel direction angle β.

A previous study by the authors suggests the possibility of a range of optimal peel angles (α=45°±15°) where peeling force is minimized [1]. Data also suggests that the width of a peeling line is proportional to the peeling force; larger peel line's widths require higher peeling forces [1, 2]. Therefore, we hypothesize that there should exist for every semi-rigid package, a theoretical optimal path that follow the midpoints of the shortest peel lines at an inclination of α. This theoretical optimal path/angle combination results in the lowest effort from the user.

It has been suggested that people biomechanically adapt to a package based on package design and user characteristics (e.g. anthropometrics, range of motion, etc) [3]. If this is true, people will attempt to minimize effort by interacting with packages in ways which minimize forces to overcome, motion, and discomfort. According to the human-package interaction framework [4], we hypothesize that, during an opening task, users will iterate receiving feedback from the package (i.e., demand of physical effort, discomfort, pain, etc.) via perception and cognition (touch and comprehension) and will act accordingly (i.e., adapting their pulling strategy and direction) to achieve their goal (i.e., opening). We hypothesize people will adjust peeling direction by trying to peel on the optimal path (defined by β) at an optimal peel angle (defined by α).

There is a need to study this user behavior in a context and tasks that reflects a real-life scenario. Research presented in this article used a motion capture system for such undertaking. Kinematics studies often require participants to adopt specific positions and to follow specific procedures to perform the task under study [5-7]. Bush *et al.* (2012) analyzed the effect of restraining a jar during opening and concluded that placing constraints is problematic because restrictions produce data that may not represent a realistic practice [8]. For that reason two testing conditions were studied.

6.2. Objectives

The objectives of this study are as follows:

1) To evaluate peel angle (α) and peel direction angle (β) during realistic conditions of opening for a lidded tray.
2) To evaluate the effects of experimental setup (i.e., restrained or unrestrained) on peeling direction during tray opening.

6.3. Materials and methods

A motion capture system was used to measure peel angles and peel direction angles during three opening tasks under two experimental setups.

6.3.1. Participants

Eligibility criteria to participate in the study included being older than 18 years old and having no history of hand disorders (IRB approval #09-179). Participants were recruited from the Lansing area (MI, USA) and all provided consent.

6.3.2. Packages

One hundred forty four lidded trays were used (16 participants × 3 tasks × 3 replicates). Trays were thermoformed by Perfecseal® (Oshkosh, WI) using mold for "Medtronic Inc. outer tray part number 350215-001", and blue tint uncoated PETG, preform thickness of 0.025 inches. Trays were sealed with PTH-017 seal coated 1073B Tyvek® die cut lids (Amcor Flexibles Healthcare, Madison, WI) using a CeraTek MD-2420 shuttle-style heat sealer (SencorpWhite, Hyannis, MA). Lids were white with no printing on them. The sealed trays had a triangular tab with a height of 12.5 mm (Fig. 6.2) that was covered with blue masking tape (3M Scotch-Blue™ Painter's Tape for Multi-surfaces) to clearly indicate which corner had to be grabbed. Every package was filled with 45 grams of corn kernels to simulate contents.

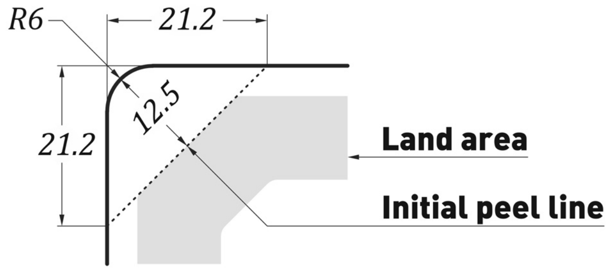

Figure 6.2 – Tab dimensions in mm, tab's surface area 217 mm^2.

The heat sealer temperature was 150°C, the pressure was 70 psi, and the cycle time was 3 seconds. After sealing, trays were visually inspected for defects according to ASTM F1886 Standard Test Method for Determining Integrity of Seals for Medical Packaging by Visual Inspection [9]. Trays with visible defects were removed. Each tray was identified by a code consisting of a sealing position (from A, top left cavity, throughout I, bottom right cavity) and run number.

6.3.3. Markers and motion tracking

A six-camera Qualisys Motion System (Gothenburg, Sweden) was used in conjunction with retro-reflective markers to capture 3D coordinate measurements of key package locations. Ten retro-reflective markers 4 mm in diameter were attached to each package (Fig. 6.3). Four markers (L1, L2, L3, and L4) were placed on one corner of the lid to define the lid plane. Six markers (T1, T2, T3, T4, T5, and T6) were attached to the tray to define the plane containing the top of the land area on the tray. Since the chosen tray could be opened by two corners, there were two marker configurations termed "left-corner" and "right-corner", discussed next.

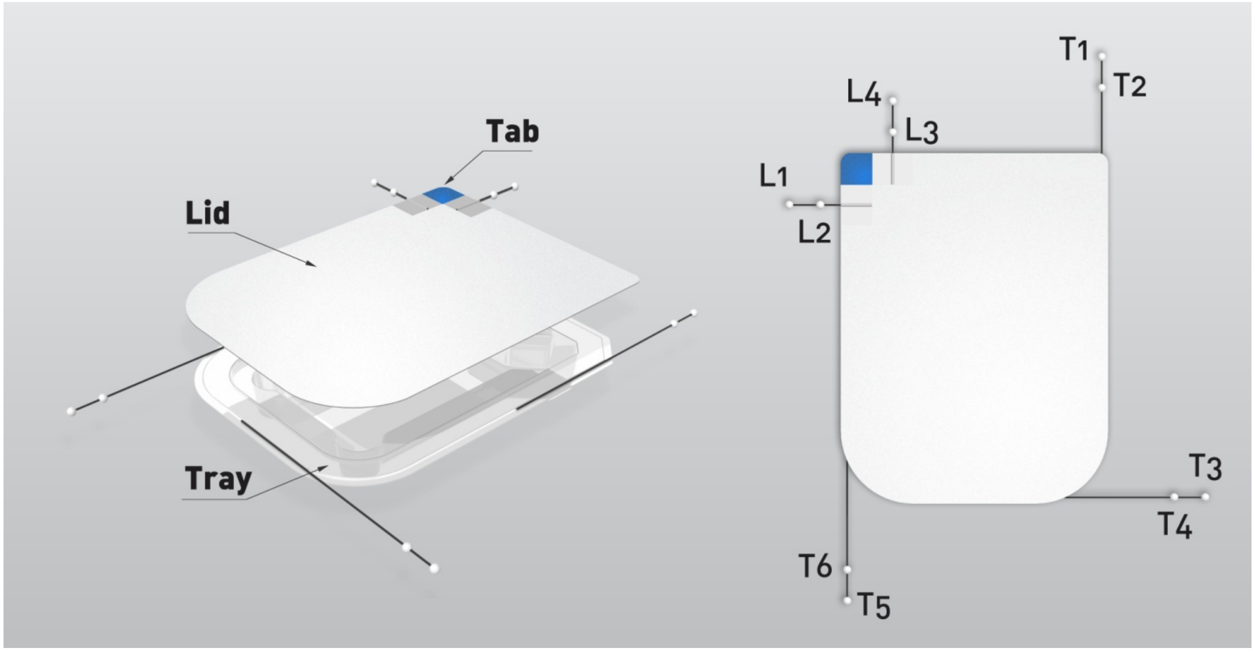

Figure 6.3 – Placement of the 10 retro-reflective markers for a “left-corner” tray configuration.

6.3.4. Procedure

Subjects were screened for any history of injury to the hands, arms or shoulders prior to the consent process. After obtaining consent, participants completed a questionnaire that collected information on gender, age, and hand dominance.

Participants stood behind a counter of a fixed height (80 cm) and completed three opening tasks. The first task consisted of opening three lidded trays with no markers to familiarize the user with the opening mechanism and to determine which of the two tabs (left or right) was chosen more often. This preference determined the marker configuration for the next task. During the second task, termed “unrestrained opening” (Fig. 6.4), participants opened three trays with markers while holding the tray.

One tray at a time was placed on the table in a consistent orientation approximately 35 cm from the counter edge closer to the participant (Fig. 6.4A).

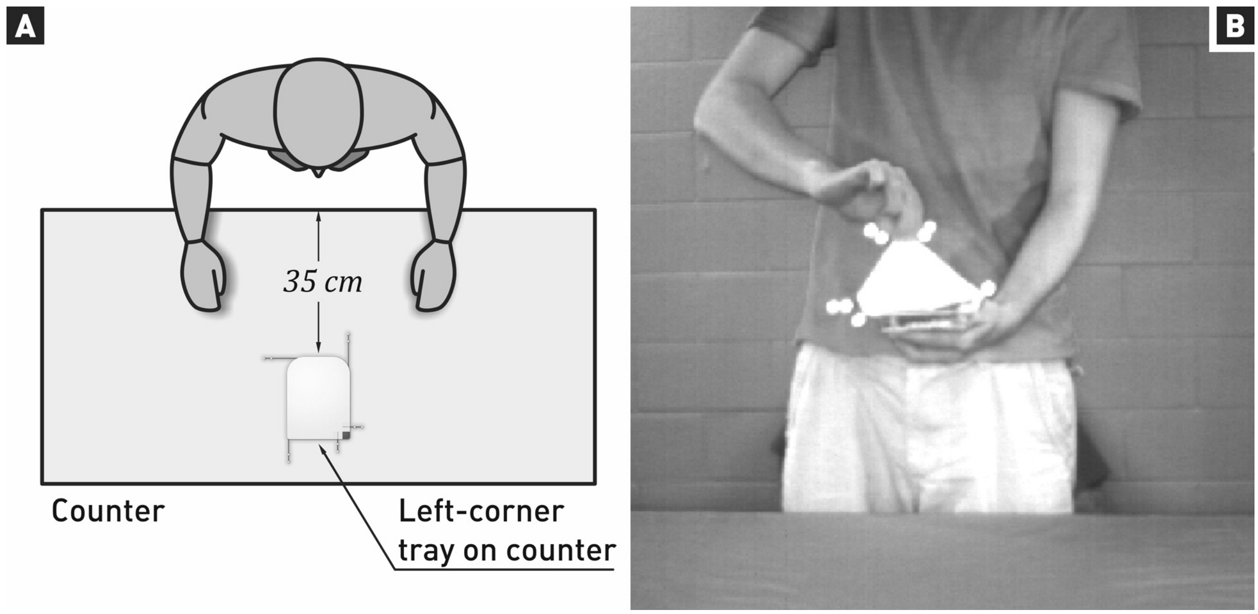

Figure 6.4 – Unrestrained opening task: (A) Top view of the experimental setup, (B) Participant opening a “left-corner” tray.

Participants were asked to pick up the tray, to hold the bottom part of the tray with one hand, to grip the tab with the other hand, and to peel the lid off completely without stopping.

The third task, termed “restrained opening” (Fig. 6.5), consisted of opening three more trays with markers; however, this time each tray was attached to the counter’s surface by means of a fixture to avoid its rotation and translation (Fig. 6.5B). Participants were instructed to hold the fixture from one of its vertical handles with the nondominant hand and to grasp the tab with her/his dominant hand. The fixture was firmly attached to the table and allowed opening using the right or left hand. Right-handed participants openened trays with the "left-corner" configurations while left-handed participants used the "right-corner" configuration. Before opening, participants were invited to tray the experimental setup and asked if it was conformable for them. There were about 30 seconds between opening events to minimize any potential effects of fatigue. Approximately 5-10 seconds of data was collected at 60 Hz using the motion system for each test condition, restrained and unrestrained. One video camera recorded all tasks.

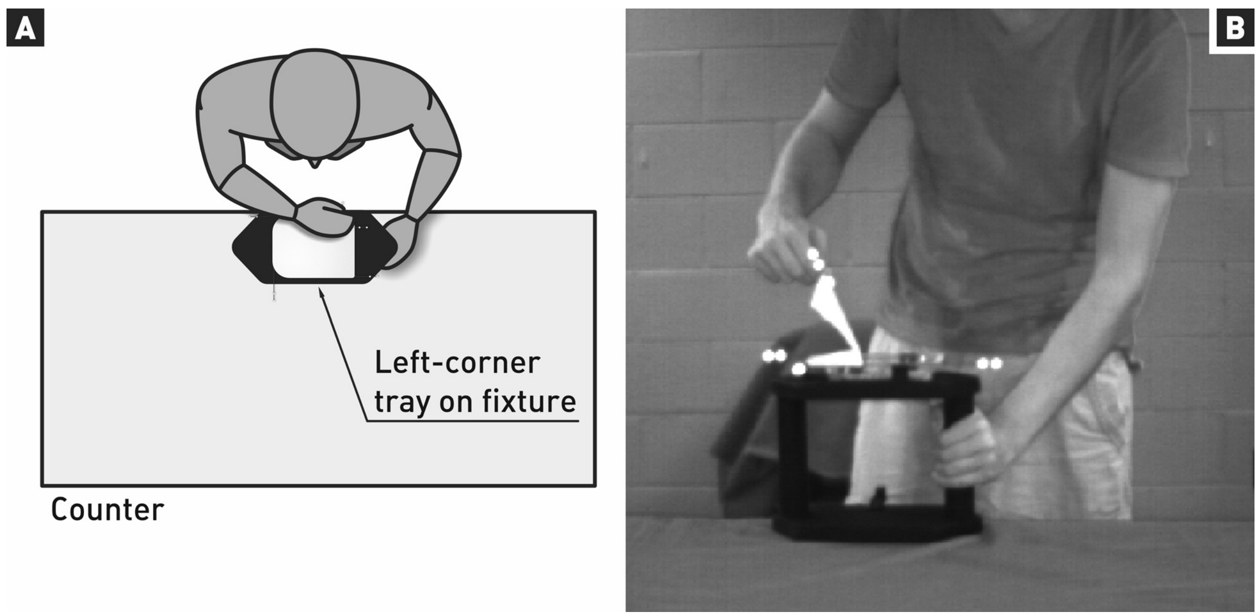

Figure 6.5 – Restrained opening task: (A) Top view of the experimental setup, (B) Participant opening a "left-corner" tray.

6.3.5. Computation of actual peeling direction

Kinematics data was used to compute the two angles that define peeling direction, peel angle α and peel direction angle β (Fig. 6.6). Each marker was named $\vec{T}_{ID}$, where *ID* is the marker's name.

$$\vec{T}_{ID} = \begin{bmatrix} T_{ID_x} \\ T_{ID_y} \\ T_{ID_z} \end{bmatrix}$$ Marker's coordinates where $ID = [L1, L2, L3, L4, T1, T2, T3, T4, T5, T6]$ (1)

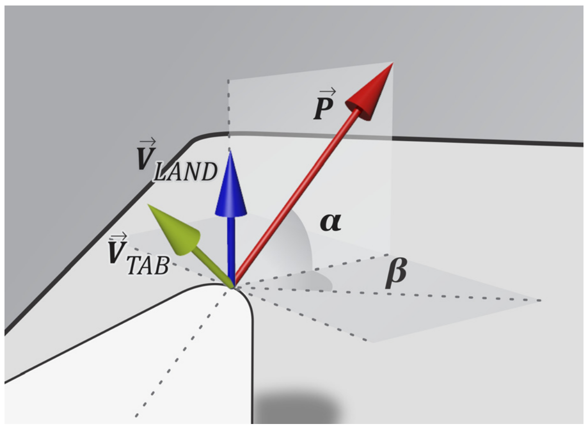

Figure 6.6 – Angles and vectors involved in the computation of peeling direction.

6.3.5.1. Peel angle α

For each frame of information, a peel angle (α) was calculated using Equation 3 which finds the angle between a normal vector to the land area or seal plane (Eqn. 1) and a normal vector to the tab (Eqn. 2). The first vector ($\vec{V}_{LAND}$) was calculated using the position of markers T1, T3, and T5 and the latter ($\vec{V}_{TAB}$) using markers L1, L2, L3, and L4.

$$\vec{V}_{LAND} = \left(\vec{T}_{T1} - \vec{T}_{T3}\right) \times \left(\vec{T}_{T3} - \vec{T}_{T5}\right)$$ Vector normal to the land area (1)

$$\vec{V}_{TAB} = \left(\vec{T}_{L1} - \vec{T}_{L2}\right) \times \left(\vec{T}_{L3} - \vec{T}_{L4}\right)$$ Vector normal to the tab (2)

$$\alpha = cos^{-1}\left(\frac{V_{LAND_x}V_{TAB_x} + V_{LAND_y}V_{TAB_y} + V_{LAND_z}V_{TAB_z}}{\|\vec{V}_{LAND}\|\|\vec{V}_{TAB}\|}\right) \qquad \text{Peel angle } \alpha \qquad (3)$$

A typical peel angle against time plot is shown in Figure 6.7. The tab starts out forming a 180° angle (lid is closed). The peel angle decreases until reaching 90° at about 3.4 seconds. At this point, the change is so rapid that data shows few data points in the 120°-70° range. The next phase is defined as the actual pulling phase with angles ranging from 60° to 40° approximately.

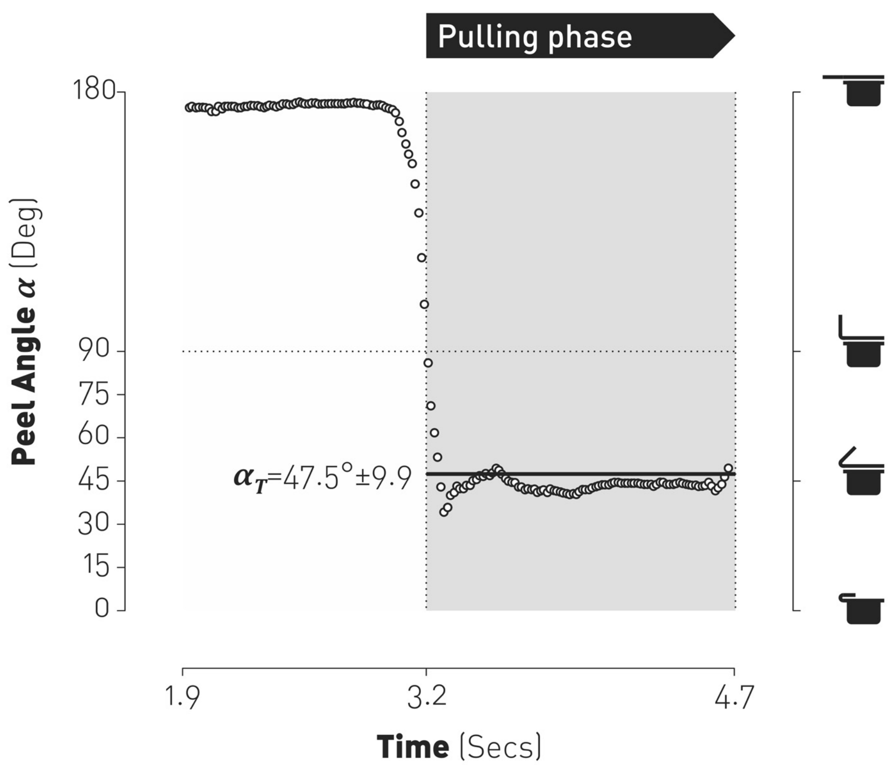

Figure 6.7 – Example of a Peel Angle α *vs*. Time plot.
Shown: Restrained opening trial #1, subject #4, and α_T.

Two specific peel angles averages were computed in order to characterize each package tested:

a) Total peel angle (α_T): defined as the average of all peel angles during the pulling phase. The pulling phase starts with the first peel angle value smaller than 90° (Fig. 6.7).

b) Initial peel angle (α_I): defined as the average of all peel angles during the first half second of the pulling phase (30 frames of data) (Fig. 6.8).

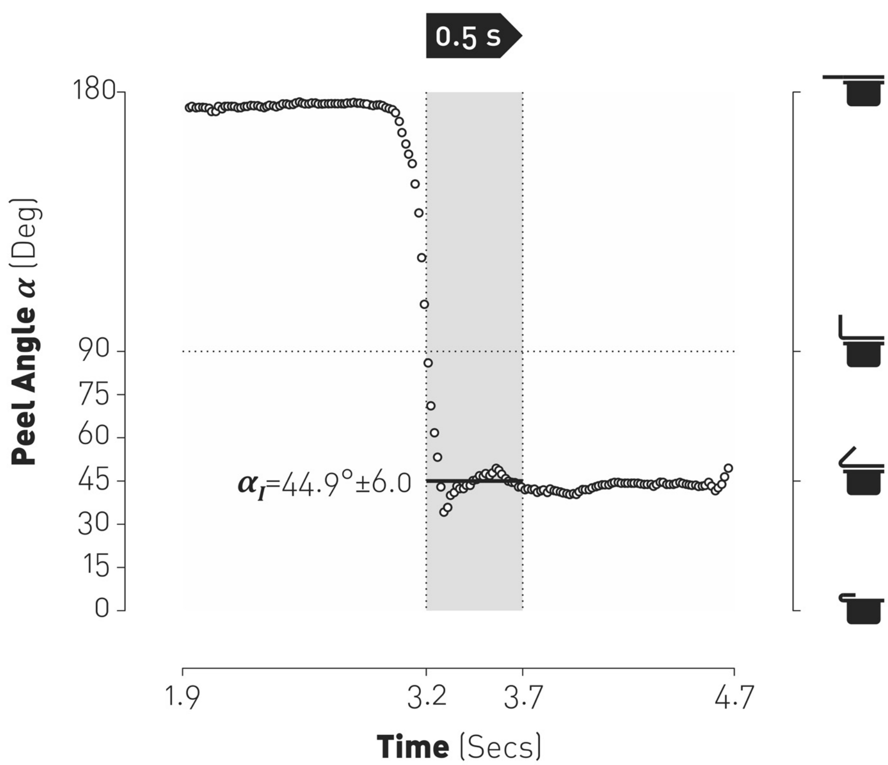

Figure 6.8 – Graphical representation of an α_I calculation.
Shown: Restrained opening trial #1, subject #4.

6.3.5.2. Peel direction angle β

A typical peel direction angle against time plot is shown in Figure 6.9.

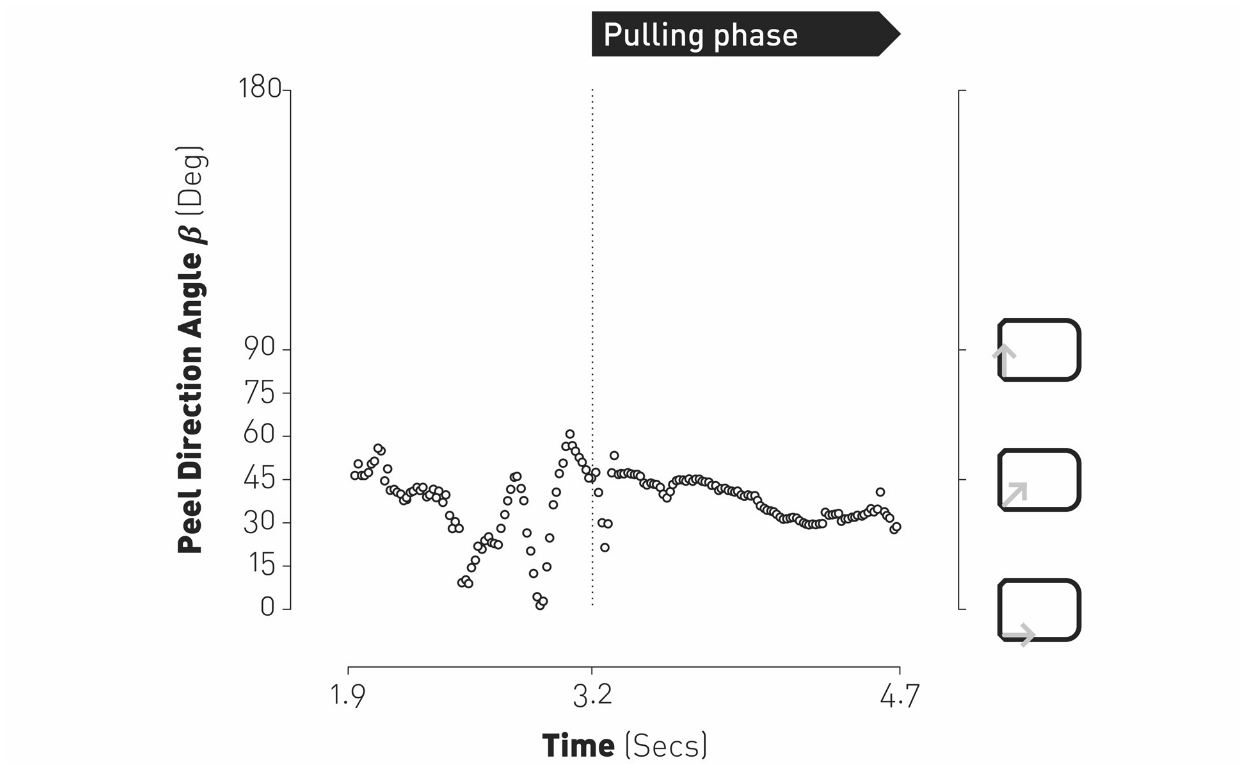

Figure 6.9 – Example of a Peel Direction Angle β *vs*. Time plot.
Shown: Restrained opening trial #1, subject #4.

Peel direction angle β was calculated using Equation 5 which finds the angle between the XY-component of the normal vector to the tab plane computed with Eqn. 2 and a line parallel to the longest tray's edge defined by a vector between markers T1 and T2 (Eqn. 4).

$\vec{V}_{TRAY} = \vec{T}_{T1} - \vec{T}_{T2}$ Vector parallel to the tray's edge (4)

$$\beta = cos^{-1}\left(\frac{V_{TRAY_x}V_{TAB_x} + V_{TRAY_y}V_{TAB_y}}{\sqrt{V_{TRAY_x}{}^2 + V_{TRAY_y}{}^2} \cdot \sqrt{V_{TAB_x}{}^2 + V_{TAB_y}{}^2}}\right) \quad \text{Peel direction angle } \beta \qquad (5)$$

One specific peel direction average was computed in order to characterize each package tested. The initial peel direction angle (β_I) is defined as the average of all peel direction angles during the first half second (30 frames of data) of the pulling phase (Fig. 6.10).

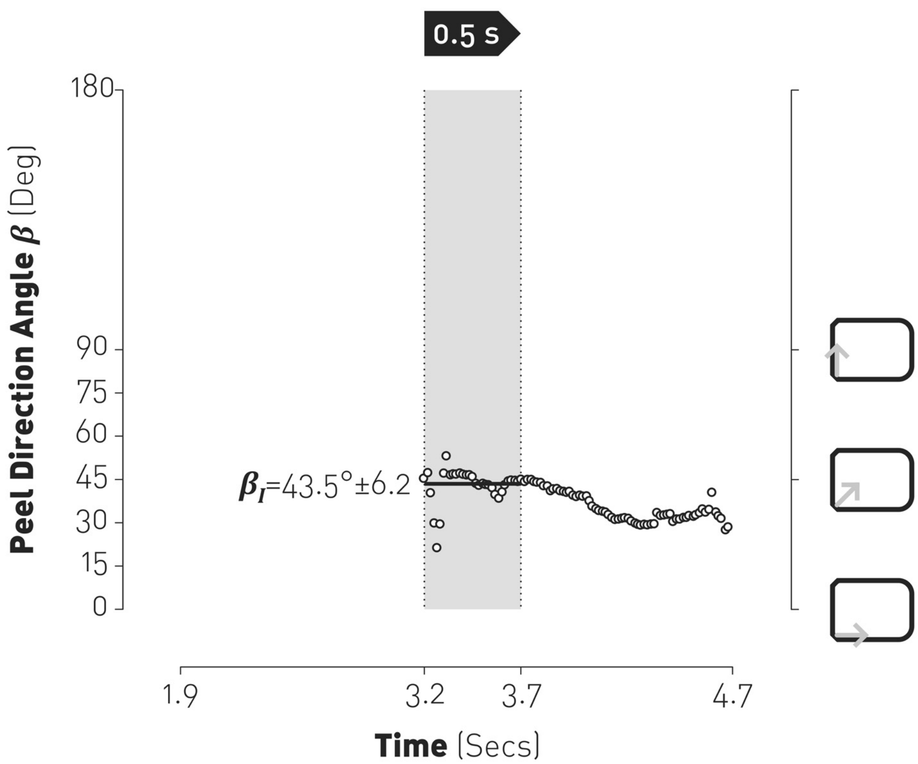

Figure 6.10 – Graphical representation of a β_I calculation.
Shown: Restrained opening trial #1, subject #4.

6.4. Results

6.4.1. Participants

Sixteen participants completed the three opening tasks. Average age of the panel was 30 years (*sd*=7, *min*=19, *max*=43). Nine males and seven females; all participants were right handed. During the first opening task people were very consistent when choosing the left or the right tab. With only one exception, all participants choose the same tab in each of the three trays. Based on the first opening task, six participants opened a left-corner configuration and 10 right-corner trays during the unrestrained opening. For the restrained opening condition*, o*nly left-corner trays were tested because all right-handed participants opted for this configuration.

6.4.2. Opening time

Opening time was defined as the total time that a participant took to completely peel off the lid of a tray. It starts when the participant has grabbed the tab and starts pulling and finalizes in the moment when the lid is separated from the tray. Both start and end points were defined by watching video recordings from each opening trial. A mean opening time for each participant was calculated using the opening times of three opening events (three replicates). Figure 6.11 shows mean opening times for each participant for both experimental setups and a general mean opening time for each opening condition. An independent-samples t-test comparing the mean opening times of both experimental setups found a significant difference between the means of the two conditions ($t(80)=1.66$, $p<0.001$). The mean of the unrestrained condition was significantly higher (*m*=4.6 s, *sd*=2 s, *min*=1.3 s, *max*=9.7 s,) than the mean of the restrained opening condition (*m*=3.4 s, *sd*=1.3 s, *min*=1 s, *max*=7.6 s).

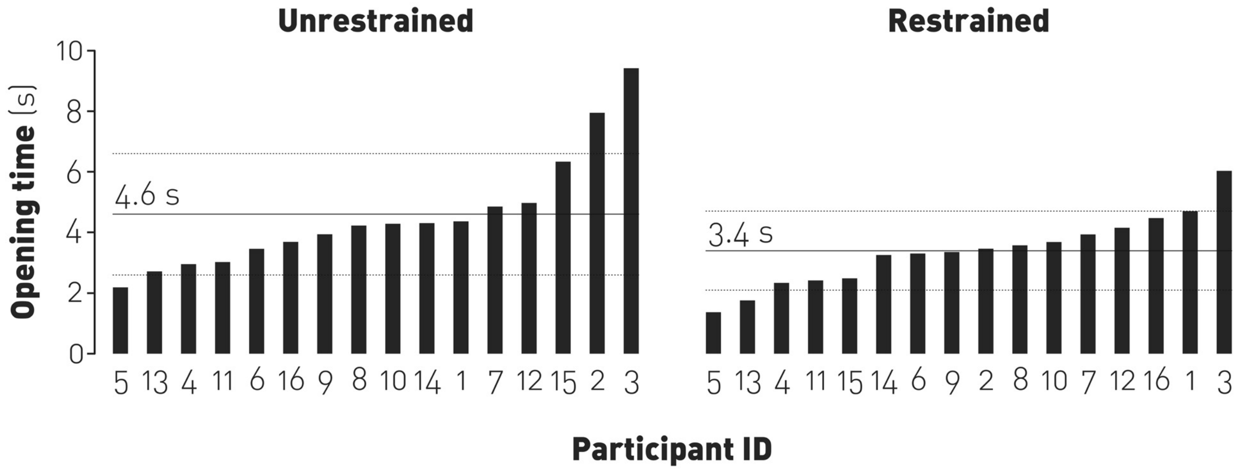

Figure 6.11 – Average opening time for each participant in both experimental setups. The horizontal lines represent the mean opening time and one standard deviation from it.

6.4.3. Peel angle α

The average maximum peel angle α measured across all 48 trials (16 participants x 3 replicates) was 178.9° (*sd*=0.9°) for the unrestrained condition and 178.8° (*sd*=1.1°) for the restrained condition. This value corresponds to the situation in which the tray's lid is completely sealed before the participant starts opening. The minimum average peel angle was 23° (*sd*=12°) for the unrestrained setup and 32° (*sd*=16°) for the restrained opening condition.

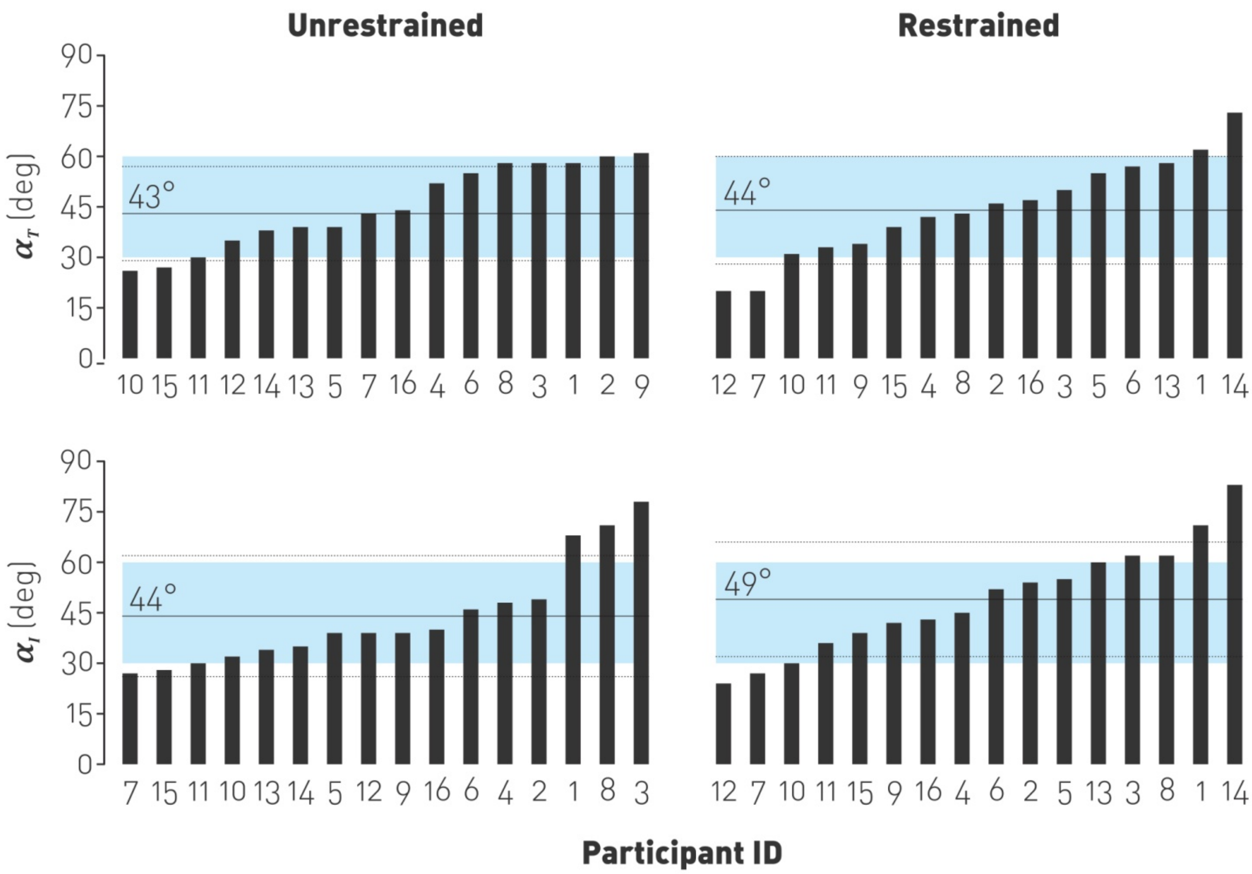

Figure 6.12 – Average total peel angle (α_T) and average initial peel angle (α_I) for each participant in both experimental setups. The horizontal lines represent the mean peel angle and one standard deviation from it. The blue area represents the optimal peel angle range (α=45°±15°).

Mean total peel angle (α_T) and mean initial peel angle (α_I) were calculated for each participant using three replicates. Figure 6.12 shows these peel angle means for each participant, for both experimental setups, and general means for each opening condition. For the unrestrained opening condition, the mean total peel angle (α_T) across all participants was 43° (*sd*=14°, *min*=20°, *max*=66°) and the mean initial peel angle ($\bar{\alpha}_I$) was 44° (*sd*=18°, *min*=20°, *max*=81°). For the restrained opening condition, the mean total peel angle (α_T) was 44° (*sd*=16°, *min*=15°, *max*=79°) and the mean initial peel angle (α_I) across all participants was 49° (*sd*=17°, *min*=18°, *max*=86°).

Independent-samples t test were computed to determine the following:

- No significant differences were found between mean total peel angle (α_T) and mean initial peel angle (α_I) for both opening conditions: unrestrained ($t(93)=1.661$, $p=0.419$) and restrained ($t(93)=1.661$, $p=0.085$).
- No significant difference was found between mean total peel angle (α_T) for both opening conditions ($t(93)=1.661$, $p=0.351$). The mean for the unrestrained condition (α_T =43°, *sd*=14°) was not significantly different from the mean of the restrained condition (α_T =44°, *sd*=16°).
- No significant difference was found between mean initial peel angle (α_I) for both opening conditions ($t(93)=1.661$, $p=0.078$). The mean for the unrestrained condition (α_I=44°, *sd*=16°) was not significantly different from the mean of the restrained condition (α_I=49°, *sd*=17°).

6.4.4. Peel direction angle β

Mean initial peel direction angles (β_I) were calculated for each opening condition and for each participant using three replicates. Figure 6.13 shows mean initial peel direction angles for each participant for both experimental setups and a general mean peel direction angle for each opening condition. An independent-samples t-test comparing the mean initial peel direction angles of both experimental setups found a significant difference between the means of the two conditions ($t(76)=1.665$, $p<0.001$). The mean of the restrained condition was significantly lower (m=34°, sd=13°, min=3°, max=70°) than the mean of the unrestrained opening condition (m=48°, sd=22°, min=2°, max=89°).

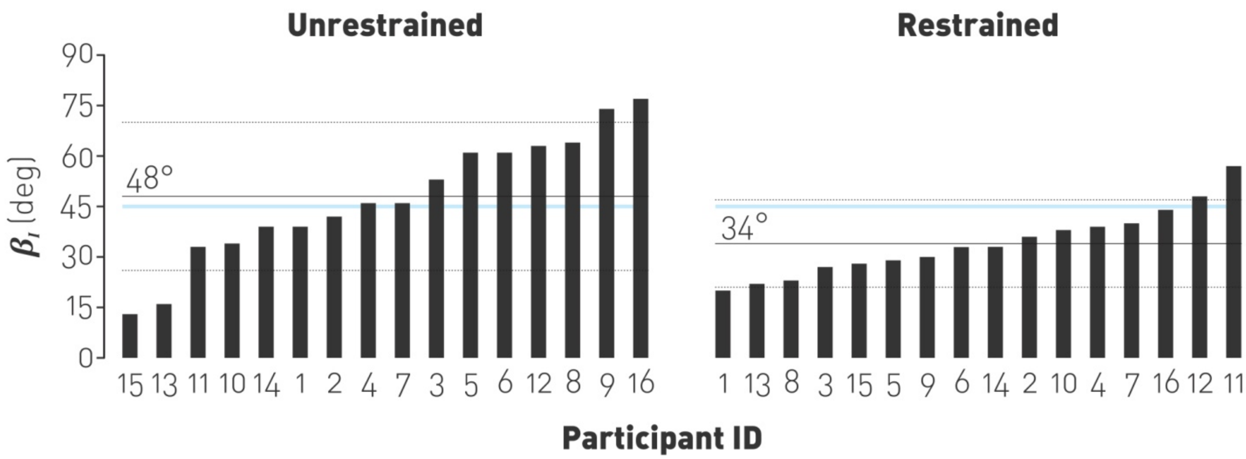

Figure 6.13 – Average initial peel direction angle (β_I) for each participant in both experimental setups. The horizontal lines represent the mean peel angle and one standard deviation from it. The blue line represents the optimal peel direction angle (β=45°) at the beginning of the opening task.

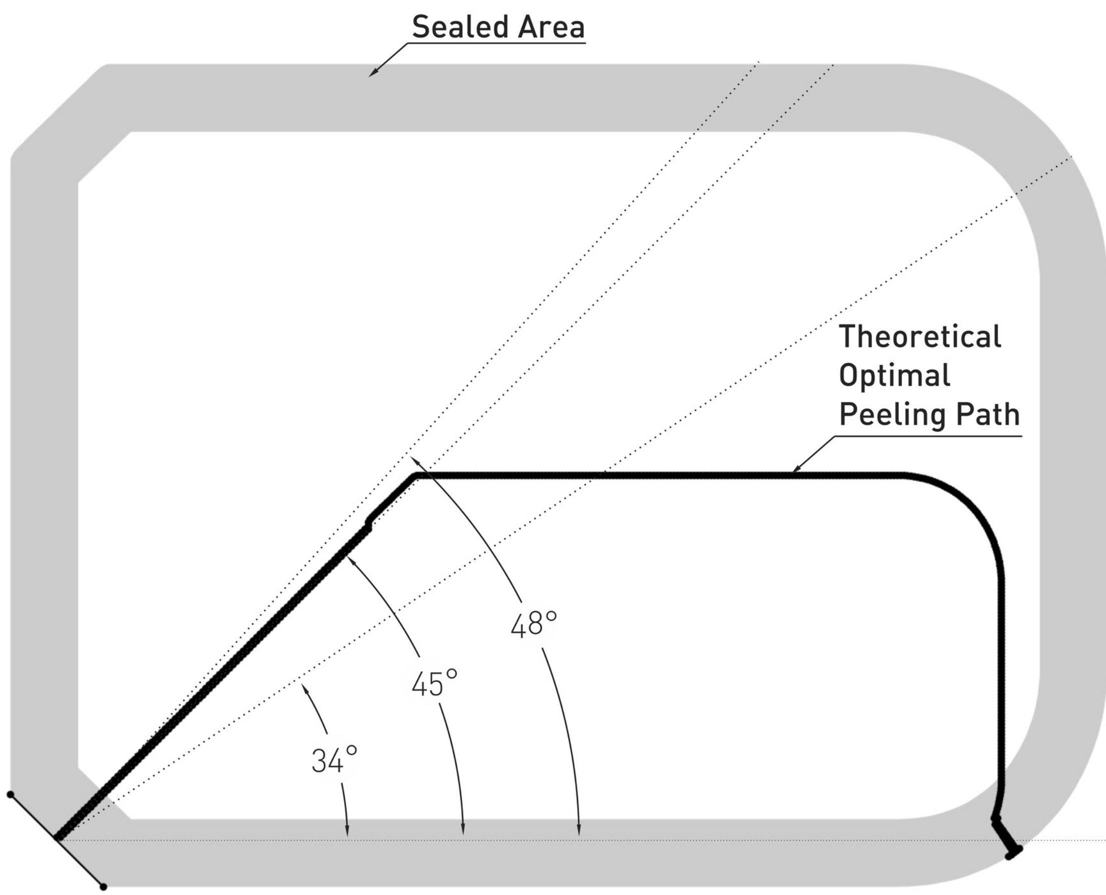

Figure 6.14 – Comparison of initial peel direction angle (β_I) for the restrained condition (β_I =34°±13°), unrestrained condition β_I =48°±22°, and the theoretical optimal peeling path (β_I =45°).

6.4.5. Missing frames

A missing frame is the consequence of not capturing a crucial marker so the calculation for that frame cannot be done. The restrained opening condition had only a 1% of missing data (109 out of 9835 frames). For the unrestrained condition the total of missing frames accounted for 8% (1025 out 13180 frames). As expected, the unrestrained condition was more challenging in terms of avoiding missing frames. This is because participants had the freedom to open the tray as they wish and sometimes body parts (i.e., finger, hand, and forearm) or the lid covered a marker for a fraction of a second. Fortunately, many of the missing frames were located in the pre-pulling phase that was not used for calculations. Missing data did not pose significant problems for calculations for neither of the two conditions.

6.4.6. Experimental setup comparison

As presented earlier, experimental setup had a significant effect on opening time and peel direction angle but did not have a significant effect on peel angle. In addition, as expected, the unrestrained opening condition had a higher percentage of missing frames than the restrained condition. Table 6.1 summarizes the comparison between setups.

Table 6.1 – Comparison of results between experimental setups.

Variable	Experimental setup		p-value
	Unrestrained	Restrained	
Missing frames	8%	1%	
Opening time	4.6 s ± 2.0 s	3.4 s ± 1.3 s	<0.001
Total peel angle (α_T)	43° ± 14°	44° ± 16°	0.351
Initial peel angle (α_I)	44° ± 18°	49° ± 17°	0.078
Initial peel direction angle (β_I)	48° ± 22°	34° ± 13°	<0.001

6.5. Conclusions and discussion

A motion capture system was used to measure peel angles (α) and peel direction angles (β) during an opening task under two experimental setups. Experimental setup had an effect on opening time and peel direction angle but did not have a significant effect on peel angle. On average, participants used peel angles and peel direction angles close to the hypothesized values (α=45±15° and β=45°).

The four peel angle α measurements (43°, 44°, 44°, and 49°) fall in the optimal peel angle range (α=45°±15°) in which pulling force is minimize suggesting that, on average, most of the participants used angles within these optimal limits during the entire opening task. For the restrained opening condition, between 62-75% of all participants used peel angles within optimal range (10 out of 16 persons for α_I and 12 out of 16 for α_T). For the unrestrained opening condition, between 69-81% of all participants used peel angles within optimal range (11 out of 16 persons for α_I and 13 out of 16 for α_T).

The initial peel direction angle β_I measured during the unrestrained opening condition (β_I=48°, sd=22°) approximated the theoretical angle of β=45° confirming that most participants pulled the tab in this direction during the initial stages of the opening task (Fig. 6.14). The initial peel direction angle β_I measured with the restrained opening condition (β_I=34°, sd=13°) was significantly lower but still in the range if standard deviation is considered. One possible interpretation of this lower value is that the restrained opening setup works like a one-handed task while the unrestrained condition requires the coupled action of both hands. In the restrained setup, while the non-dominant hand grabs the fixture from one of the vertical grips, the dominant hand, which is peeling the lid, makes a movement describing and arc. This movement might be reducing the peel direction angle.

The difference between of opening times between opening conditions might be explained by the degree of difficulty of opening a tray that is fixed to a table compared to holding the same tray with one hand, peeling its lid with the other hand, while attempting to not spill the contents (corn kernels). This higher degree of difficulty might add approximately more than one second in average to the time of each opening event.

In conclusion, we hypothesize people adjust peeling direction by trying to peel on the optimal path (defined by β) at an optimal peel angle (defined by α). This study provides evidence that most participants pulled the tab of a tray in an optimal peel angle direction during the beginning of the opening tasks and peeled its lid at an optimal peel angle inclination. Further analysis of the data collected will provide more evidence regarding the entire peeling path.

6.6. Limitations

The placement of the retro-reflective markers was challenging. It was difficult to position them in a fashion that did not interfere with user's behavior but, at the same time, remained visible by at least three of the six infrared cameras. Targeting attempted to minimally impact the user while enabling measurement, but it is obvious that a package with no markers would be the ideal.

6.7. Acknowledgements

The authors would like to thank Amcor Flexibles for providing the lids, and Perfecseal for providing the thermoformed trays used this study. We also would like to thank the people who volunteered their time to participate in this study.

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7

Tab size and grip choice

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Abstract

The action of opening flexible and semi-rigid packaging is characterized by grasping and pulling with the fingertips. In a common pulling action for peeling back, one hand holds the package while the other pinches an area of the package (i.e., a tab) between the thumb and one or more of the other fingers. Typically there are three grip types employed: pulp pinch (PP), chuck pinch (CP), and lateral pinch (LP). The ability to exert force with fingers and thumbs is directly related to these three grip styles. LP allows more force to be applied than CP and PP. Moreover, CP grip allows more force than PP grip. It is assumed that LP and CP need more gripping space than PP so the size of a tab conditions grip choices. Therefore, the objective of this experiment is to test the hypothesis that tab size affects grip choices.

Sixteen subjects with no history of injury to the hands, arms, or shoulders participated in two opening tasks. The first task consisted of opening three screening trays to familiarize the user with the opening mechanism and to determine which of the two tabs (left or right) each user chose more often. This preference determined the tab configuration (left or right corner tab) during kinematic testing. During the second task participants opened six testing trays with different trapezoidal tabs in random order. Tab height ranged from 5 mm through 30 mm in 5 mm intervals. Participants were characterized by gender, age, and hand dominance. Pictures of two postural preferences (clasped hands and folded arms) were taken to characterize laterality. Two high definition video cameras recorded the second task. Video recordings were analyzed to measure opening times, time spent on each grip style (PP, CP, and LP), and the initial grip used.

No significant differences were found between tab size, initial grip, and pulling grip. Lateral pinch was predominantly used as initial grip and in particular as pulling grip. An unexpected finding was the significant relationship between laterality patterns and corner preferences.

Key words

Peelable seal, peeling, tab size, grip, usability

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7.1. Introduction

The action of opening flexible and semi-rigid packaging is characterized by grasping and pulling with the fingertips. This type of grasping yields much smaller forces than pulling while grasping with both the palm and fingers [1]. In a common pulling action for peeling back, one hand holds the package while the other pinches an area of the package (tab, tag, flap, tear strip, etc.) between the thumb and one or more of the other fingers. There are three grip types involved [1-3]:

a) Pulp pinch (PP) (Fig. 7.1A): a grasp in which the tip of the thumb is pressed against the tip of the index finger. It's also called tip pinch or pulp 2 pinch.
b) Chuck pinch (CP) (Fig. 7.1B): grip using the tip of the index and middle fingers on one side and the pad of the thumb on the other side, acting in opposition. It is also called palmar pinch or three jaw chuck pinch.
c) Lateral pinch (LP) (Fig. 7.1C): finger prehension using the pad of the thumb and the lateral side of the middle phalanx of the index finger. It is also called key pinch.

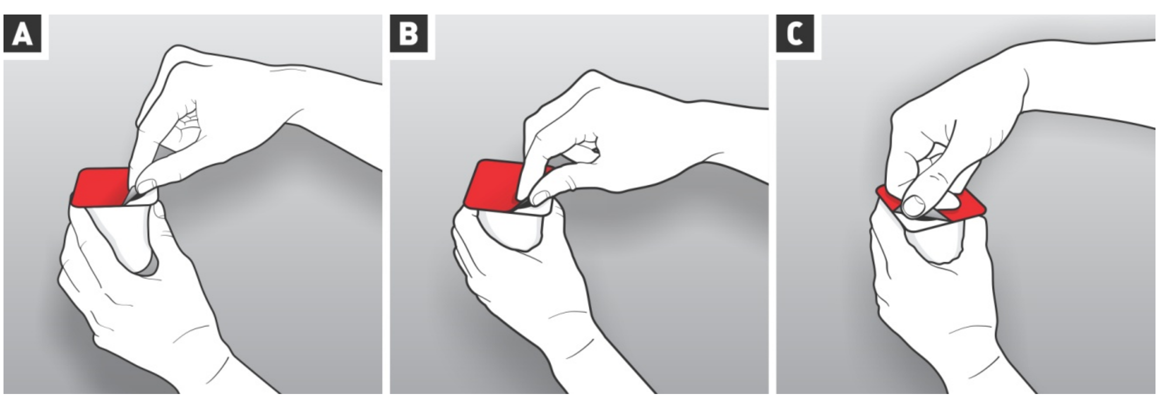

Figure 7.1 – The three grip types involved in peeling back tabs: (A) Pulp pinch, (B) Chuck pinch, and (C) Lateral pinch.

The ability to exert force with fingers and thumbs is directly related to these three grip styles (Fig. 7.2). Lateral pinch (LP) allows more force to be applied than chuck pinch (CP) and pulp pinch (PP) [1, 4], whereas CP grip allows more force than PP grip [1, 5].

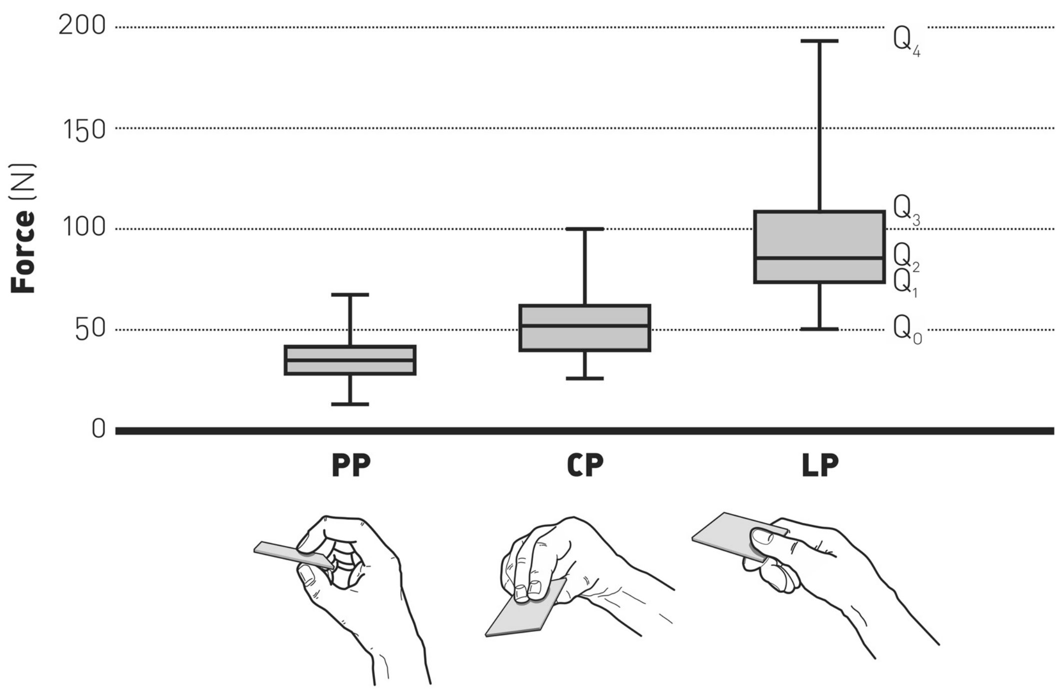

Figure 7.2 – Box-plots of pull-tear forces for three types of pinch.
PP: pulp pinch; CP: chuck pinch; LP: lateral pinch.
Q_0 and Q_4 are the minimum and maximum values. Q_1, Q_2 and Q_3 are the other three quartiles. Adapted from Imrhan (1987).

Not only is force needed to perform basic manipulations, but it is also related to joint stress and discomfort. A study on grips used in packaging openability using computer simulation has suggested that users might avoid certain grip styles (e.g., pulp pinch) because higher forces produce higher stress in joints causing pain or discomfort

[3]. Other types of grips (e.g., lateral grip) transmit lower forces on joints making users, in particular older ones, less likely to suffer pain [3].

Yoxall's observational study of 50 users showed that 54% used a CP grip to peel a lid of a yogurt pot, 26% used PP, and 20% used LP [3]. For the three grip types, pulling away from the body was more popular than pulling towards it [3]. The DTI's observational study on flexible packaging opening identified two user strategies (package held on a work surface or in hand) and two techniques (straight pulling and rotating the wrist) in conjunction of the three grip types mentioned [2].

According to the human-package interaction framework described by de la Fuente *et al.* [6], it is hypothesized that, during an opening task, users will iterate receiving feedback from the package (i.e., tab size) via perception (touch and vision) and will act accordingly (i.e., adapting their grip strategy) to achieve their goal (i.e., opening). If people biomechanically optimize themselves, they will tend to use the most powerful grip that the design allows. If this is true, space available for gripping on a package would condition their choices.

7.2. Objective

The objective of this experiment was to test the hypothesis that tab size affects grip choices.

7.3. Materials and methods

7.3.1. Participants

Eligibility criteria to participate in this study included being older than 18 years old and having no history of hand disorders (IRB approval #09-179). Sixteen participants were recruited from the Lansing area (MI, USA). The average age of the panel was 30 years (*sd*=7, *min*=19, *max*=43) and consisted of nine males and seven females. All of them were right handed.

7.3.2. Packages

One hundred forty four lidded trays were used (16 participants × 3 screening packages × 6 tab treatments). Trays were thermoformed by Perfecseal® (Oshkosh, WI) using mold for "Medtronic Inc. outer tray part number 350215-001", and blue tint uncoated PETG, preform thickness of 0.025 inches. Trays were sealed with PTH-017 seal coated 1073B Tyvek® die cut lids (Amcor Flexibles Healthcare, Madison, WI) using a CeraTek MD-2420 shuttle-style heat sealer (SencorpWhite, Hyannis, MA). Every package was filled with about 45 grams of corn kernels to simulate contents. Lids were white with no printing on them. There were two types of trays: screening and testing. Screening trays had two triangular tabs available for opening and no color indicating where the tabs were. Testing trays had a trapezoidal tab in one corner (right or left corner) (Fig. 7.3) that was covered with blue masking tape (3M Scotch-Blue™ Painter's Tape for Multi-surfaces) to clearly indicate which corner had to be grabbed. Testing trays had six tab sizes. Tab height ranged from 5 mm through 30 mm with 5 mm intervals (Fig. 7.4). All tab treatments had the same starting peel line width so they had the same starting peeling force which ranged from 7.5 N (at α=0°, *sd*=0.6) through 4.3 N (at α=45°, *sd*=0.4).

Figure 7.3 – Test trays: (A) Tab on left corner, (B) Tab on right corner.

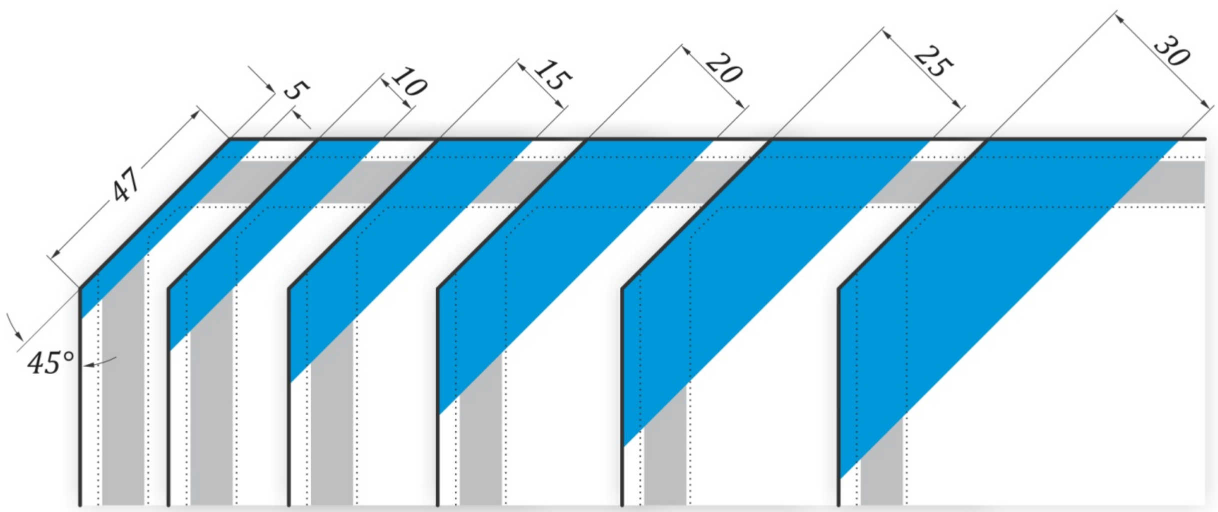

Figure 7.4 – Tab dimensions in mm.

The heat sealer temperature was 150°C, the pressure was 70 psi, and the cycle time 3 seconds. After sealing, trays were visually inspected for defects according to ASTM F1886 Standard Test Method for Determining Integrity of Seals for Medical Packaging by Visual Inspection [7]. Trays with visible defects were removed. Each tray was identified by a code consisting of a sealing position (from A, top left cavity, throughout I, bottom right cavity) and run number.

7.3.3. Procedure

Subjects were screened for any history of injury to the hands, arms or shoulders prior to the consent process. After obtaining consent, participants completed a questionnaire that collected information on gender, age, hand dominance, and postural preferences.

7.3.3.1. Postural preferences

Hand clasping (HC) and arm folding (AF) were recorded with a digital picture (Fig. 7.5). For HC, every participant was requested to clasp their hands with the fingers interlaced. Preference was coded from the pictures with respect to the thumb in the uppermost position. For AF, subjects were requested to fold their arms. Again, preference was coded by the arm-on-top position.

Figure 7.5 – Hand clasping: (A) Right-thumb-top and (B) Left-thumb-top. Arm folding: (C) Right-arm-top and and (D) Left-arm-top.

For statistical analysis, subjects were divided into four groups according to their uppermost arm and thumb position (Table 7.1). Based on Mohr *et al.* classification, groups RR and LL are referred to as displaying a “congruent" pattern, and groups RL and LR as displaying an “incongruent" pattern.

Table 7.1 – Classification of postural preferences.[8]

Pattern	Group	Arm folding (AF)	Hand clasping (HC)
Congruent	RR	Right arm top	Right thumb top
	LL	Left arm top	Left thumb top
Incongruent	RL	Right arm top	Left thumb top
	LR	Left arm top	Right thumb top

7.3.3.2. Fingers and hand dimensions

A photographic method used in previous studies was employed to characterize the anthropometrics of each subject [9]. A folding camera holder was used to capture digital images of each subject’s hands. It consists of an articulated arm with a flat base. A 10 mm square grid is printed on the base. The top of the foldable arm had a digital camera mounted to a fixed distance from the board (Fig. 7.6).

Figure 7.6 – Folding camera holder.

Every participant was asked to place their hand on the grid, spreading their fingers. Four different pictures for each hand were taken: palm down, palm up, hand open with the lateral of the index finger parallel to the lens, and hand closed with the thumb parallel to the lens. Using a software for graphics, CorelDraw® [10], these pictures were scaled and parts of the hand measured. This method was chosen because of its flexibility and ease regarding data collection. Eventually the dimensions of any finger can be known if the research process requires it.

7.3.3.3. Opening tasks

Participants stood behind a counter of a fixed height (80 cm) and completed two opening tasks. The first task consisted of opening three screening trays to familiarize the user with the opening mechanism and to determine which of the two tabs (left or right) was chosen more often. This preference determined the tab configuration (left or right corner tab) for the testing trays used in the second task. During the second task participants opened six testing trays with different tab sizes. They were instructed to open each tray as they normally would. They were told that their speed did not matter and that they should wait a few seconds between packages. The six packages were stacked on the table in a randomized order for each participant. Two high definition video cameras recorded the second task. Both cameras framed the hands of the participants from different locations to guarantee a clear view of the fingers regardless of tab configuration. Video recording were analyzed to measure opening times, time spent on each grip style (pulp, chuck, and lateral pinch – see Fig. 7.7 for examples), and the initial grip used.

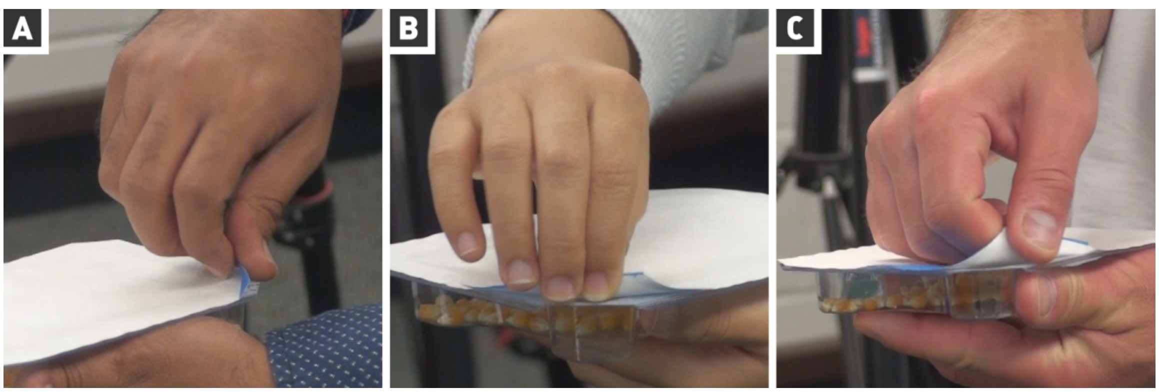

Figure 7.7 – Grip styles extracted from video recordings:
(A) Pulp pinch, (B) Chuck pinch, and C) Lateral pinch.

7.3.4. Data analysis

All data were analyzed using SPSS version 16 [11]. One-way analyses of variance (ANOVAs), chi-square test, and Fisher's exact test were computed to examine potential differences on the dependent variables related to opening time, initial grip, pulling grip, laterality, and corner preference.

7.4. Results

7.4.1. Opening time

The total average opening time was 2.8 seconds (*sd*=1.6 s). The mean opening times for each tab size were compared using a one-way ANOVA. Although mean opening times seem to decrease as tab size increases, no significant difference was found ($F(5,89)=0.404$, $p>0.05$). A summary of opening times is shown in Table 7.2.

Table 7.2 – Mean opening time for each tab height.

Tab Height (mm)	Mean Opening Time (seconds)		
5	3.1	±	1.5
10	2.8	±	1.7
15	3.0	±	1.7
20	2.9	±	1.8
25	2.4	±	1.3
30	2.6	±	1.3

7.4.2. Initial grip

For each trial, the initial grip that participants used initially to approach the tab was recorded. In some cases, subjects quickly changed their initial grip and continued with another. It was very uncommon that a subject changed grip styles more than once during a particular trial. Figure 7.8 shows the percentage of participants that used each grip style for each tab size. A visual interpretation of the figure suggest that, as tab height increases, participants seem to choose lateral pinch more and pulp pinch less while chuck pinch stays more or less constant. However, a chi-square test of independence was calculated comparing initial grip style and tab height and no significant relationship was found ($\chi^2(15)=7.835$, $p=0.930$).

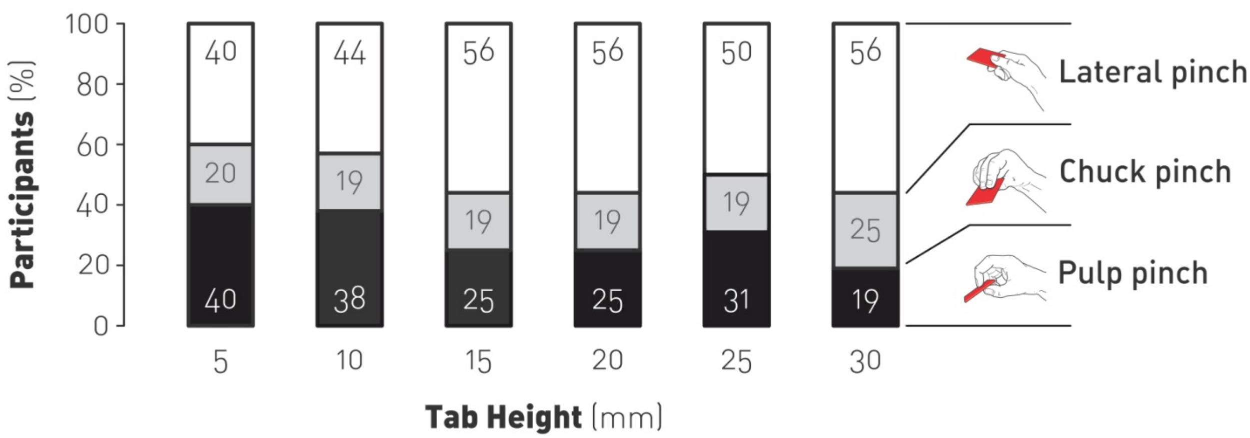

Figure 7.8 – Initial grip style for each tab size.

7.4.3. Pulling grip

For each trial, time spent on each type of grip was measured from the video recordings. Then for each tab height, a proportion of time spent on each grip was calculated in order to compare these proportions across tab heights (Fig. 7.9). Lateral pinch was used in larger proportions of time than the other grip styles during pulling regardless tab size. For tabs with height of 10 mm or more, participants tend to use less pulp pinch and more lateral pinch. However, the proportions of time on each grip style used for tabs 10 through 30 are very similar. The percentages of time by grip style for each tab size were compared using one-way ANOVA. No significant differences between tab sizes were found for pulp pinch ($F(5,89)=0.392$, $p=0.853$), for chuck pinch ($F(5,89)=0.055$, $p=0.998$), and for lateral pinch ($F(5,89)=0.245$, $p=0.941$).

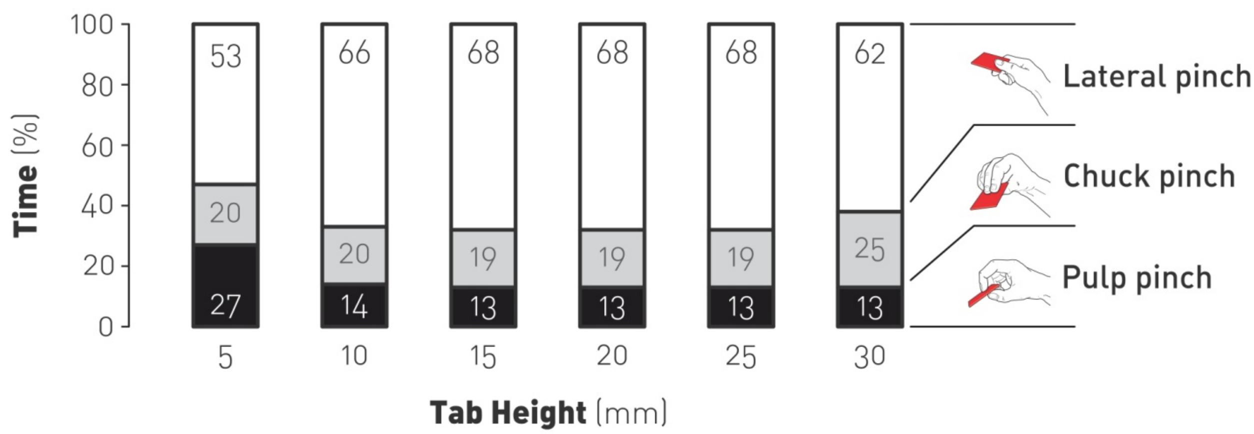

Figure 7.9 – Proportion of time spent on each grip during pulling for each tab size.

7.4.4. Postural preferences

A Fisher's exact test was used to assess whether participants' laterality pattern (i.e., congruent or incongruent) was correlated to the corner preference (i.e., right or left) used for opening the screening trays during the first opening task. Fisher's exact test yielded a $p=0.001$, suggesting that there is evidence that incongruent and congruent participants had different preferences when choosing the right or left corner of the tray. Congruent participants (LL and RR) had a tendency to open the tray from it left corner while incongruent participants (LR and RL) did so from the right corner (Fig. 7.10).

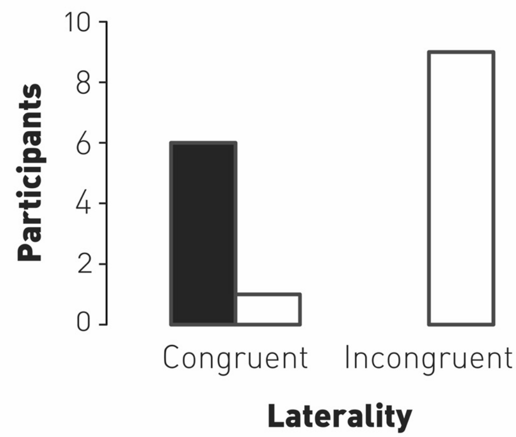

Figure 7.10 – Laterality pattern and tray's corner preference.
(■) Left corner; (□) Right corner.

7.5. Conclusions and discussion

This observational study attempted to provide evidence to support the claim that people might adapt their gripping strategy based on space available for grasping. There is not enough evidence to support that claim. However, it remains to be seen whether the trends observed in this small dataset can be found statistically significant with a larger sample population. The trends observed are as follows:

- Opening times seem to decrease slightly as tab size increase (Table 7.2).
- Initial grip seems to shift from pulp pinch to lateral pinch as tab size increase (Fig. 7.8).
- The occurrence of pulp pinch as pulling grip seems to decrease as tab size increase (Fig. 7.9)
- Between tab heights of 10-15 mm there could be a threshold beyond which gripping use patterns do not change as much (Fig. 7.8 and Fig. 7.9).

An interesting finding is that lateral pinch was predominantly used as initial grip and in particular as pulling grip. One possible explanation is that people used it because it was their stronger grip and there was enough space to use it, even with the smallest tab. An unexpected finding was the significant relationship between laterality patterns and corner preferences. Even with the small sample size the result was very clear. Finally, results could be improved with a larger sample size of participants and a more accurate software tool to measure times.

7.6. Limitations

During the analyses of the videos, for some participants it was difficult to differentiate between pulp pinch and chuck pinch. Having two cameras with different point of views solved the discrepancies in most cases. The software used to explore the videos and measure time did not provide fraction of seconds limiting the accuracy.

7.7. Acknowledgements

The authors would like to thank Amcor Flexibles for providing the lids, and Perfecseal for providing the thermoformed trays used this study. We also would like to thank the participants who took part in this study.

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8

Conclusions and future steps

It is gratifying to realize that we know more now than when we started this research project. This could have never been done without the contribution and expertise of my major professor, Dr. Laura Bix, and my always involved guidance committee members, Dr. Gary Burgess, Dr. Tammy Reid Bush, and Dr. Bruce Harte.

The main contributions can be summarized as follows:

- We have proposed the H-PIM, a comprehensive theoretical framework that helps understanding the interaction between user and packages in a holistic way.
- We have proposed an affordance-based design method targeted to one of the less developed areas regarding package design, the communication of functionally in the early stages of the H-PIM framework.
- We have a clearer picture of how peel angle affects peel force. We have developed mathematical tools to simulate and predict peeling.
- Peel angle and seal geometry have an important effect on peel force. In this regard, I suggest that once that materials and heat sealing conditions cannot be changed, seal geometry and tab design can be optimized to minimize both the force needed and the presence of high peak forces The next piece is related

to tab design, a tab must be noticeable by the user and direct him/her to perform the optimal movements to peel off the package (the peeling path depends on this and hence the force profile). It also should allow a stronger pinch that for trays seems to be the lateral pinch).

- We have been able to measure peel angles and peel direction angles during opening. Something that seemed almost impossible to do when we brainstormed the approach. More impressive was to found that people seem to use angles within optimal ranges.
- Finally, the last experiment opened more doors for questioning. It is still unclear how people decide what grip to use based on the information they receive from the package. It is really intriguing how postural preferences wired in our brain seems to be simplifying our decision making regarding package manipulations.

Possible future steps:

- To extend the relationship force/angle to others lidstock/tray combinations.
- To complete the work on optimal peeling path.
- To expand the study on tab size and grip choices.
- To research more on postural preferences and packaging manipulations.
- To investigate the effect that friction/texture on tabs might have on peel force.
- To develop a web application that incorporates the mathematical model for predicting peel force.