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A review of unilateral grippers for meat industry automation

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ABSTRACT

Background: With the expectation that meat consumption will grow by 12% over the next decade, coupled with the reported labour issues and viruses attacking human and animal health, there is a growing requirement for red meat slaughterhouse automation. Changes to current abattoir setups and processes are necessary to realise for sustainable, low-cost and scalable automation. However, to achieve such autonomous nirvana, simple, cost-efficient and robust tooling to support these systems are sought. This includes grippers used to hold, manipulate and transport workpieces, such as primal cuts of red meat, for example, with the simplest type being unilateral gripping systems.
Scope and approach: This paper critically reviews various unilateral gripping solutions available in cross-industry sectors or developed in research that could be used or adapted for the meat industry. Criteria for such tooling are simplicity, low-cost, durability and robustness, whilst being capable of gripping highly deformable objects of various structures and maintaining safety and hygiene standards. The focus is on air-driven grippers due to their ability to hold high payloads without causing visual and physical damage to the product.
Key findings and conclusions: Three pneumatic-based unilateral gripper principles, namely Coanda, Bernoulli and Vacuum, are critically reviewed for their feasibility in meat industry automation. In conclusion, the simple vacuum-based system offers the best solution of holding force and low damage thresholds. However, vacuum based design and adaption requires thought for meat surface and structure variance. This will inevitably lead to future experimental research and development work.

1. Introduction

It is the expectation that meat consumption will grow 12% by 2029. Projections for pig-meat consumption alone will see an increase to 127 Mt accounting for 28% of the total increase in meat consumption over the next decade (OCD/FAO, 2020). However, globally the meat industry continues to suffer labour shortages. In the UK, for example, 85% of businesses report recruitment difficulties within the last 12 months. UK vacancies are, on average, usually filled within 4.5 weeks. In contrast, job vacancies within the meat industry can take between 1 and 3 months, or even up to 6 months in some instances (British Meat Processors Association, 2020). In Norway, slaughterhouse workers at Røros Meat and Røros Abattoir, for example, migrate from Eastern European countries due to the lack of uptake from Norwegians to fill positions. The lack of employees is highlighted in the company's Healthy Growth Report, pointing out the lack of apprentices joining the industry as a typical challenge (Kvam & Bjørkhuag, 2015). Furthermore, employment of migrant workers has been negatively affected by not only Covid-19 travel restrictions but also having to compete with the rest of Europe for their services, with Norway often offering greater financial incentives to recruit foreign workers (Fox, 2018).

Contributing factors are the physically demanding nature of the work involved in harsh, cold, wet, slippery, and noisy environments. Also, low meat prices result in low margins and hence, the salary is often not enticing. Correspondingly, meat processing plants usually locate near good supply chain transport links, which can often be awkward locations for employees to reach.

Absenteeism is also a problem. Reports from the USA state that injuries sustained within the pork meatpacking workforce have rates of over 2.4 times the national average. For employees requiring restricted

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duties or time off work, the injury rate increases to almost three times the national average. When coupled to time off work for illnesses, including repetitive strain injuries, using Carpal Tunnel Syndrome as an example, the statistics become seventeen times the national average, equating to 60% of worker turnover per plant (Berkowitz, 2018).

Aside from labour shortages, meat shortages have been prevalent in other world regions like China, for example, after suffering an outbreak of African Swine flu (ASF). However, ASF is not limited to China, with cases in other parts of Asia, Europe, and Africa also reported (Department for Environment, 2020). China, however, is the single largest producer and consumer of pork meat. The reduction of pork consumption in China is estimated at 10%, with wholesale production down by an estimated 21% for 2019 (OCD/FAO, 2020). The impact caused by reduced meat production in ASF affected areas is low due to the increased production of other countries, including other meat sectors that make up the shortfall. However, the increased production demands on non-affected areas add further pressure on an already overwhelmed workforce.

2020 brought the emergence of a new global threat from the COVID-19 coronavirus pandemic. With the virus comes a so-called "new normal," which has seen the introduction of lockdown rules. The new guidelines included self-isolation and social distancing to combat the risk of the infection spreading. Front line workers having to carry on working included emergency services such as fire, police and medical. Also included in this list are workers of the food industry required to maintain food supplies. The conditions and layout of meat processing plants in conjunction with working processes make for poor environments to preserve social distancing measures. As a result, the proliferation of large-scale infection rates has been widespread within meat processing plants worldwide. Some examples include 140 workers in Norfolk (Barlow, 2020), 200 in Germany (Foote, 2020) and ten outbreaks resulting in 566 staff testing positive in Irish meat plants (Cullen, 2020) and according to the European Federation of Food and Tourism Trade Unions (EFFAT) report (European Federation of Food and Tourism Trade Unions, 2020), Norway has experienced closures at two red meat plants due to COVID-19 infection. Furthermore, increased travel restrictions due to COVID-19 mean that migrant labour is scarce in comparison to previous years.

Automation using intelligent machines and robots would go a long way to alleviate labour shortages, improve work conditions, as well as reducing product contamination and infection spread. The benefits of automation would also lead to increased efficiency, productivity yields and profitability (Blanes et al., 2011).

So far, the meat industry has not seen widespread automation adoption, such as that seen in other industries. There are several important reasons for this. Primarily, butchery is a manual task requiring expertise, sensory feedback and dexterous skill with a knife. These are all abilities that, although possible, can be hard to achieve using machines. Furthermore, a traditional meat processing plant, set up in a disassembly line configuration consisting of many discrete processes, requires significant investment but offers low flexibility and reliability. Such prohibitions exclude small volume markets, such as those in rural Norway with long transport distances, from investment in automated systems.

With that said, the red meat slaughter industry requires cost-effective tools to support automation, including a means for gripping that causes no damage to the product but still offers a reliable and robust operation. Furthermore, if automation of the slaughter process is to be realised by both high and low volume producers alike, then a shift in the abattoir paradigm is also needed.

An innovative approach to the slaughter process is under development in Norway. Here (Alvseike et al., 2018) and (Alvseike et al., 2020) a consortium is engaged in developing a fully robotised slaughter cell that is scalable to meet heterogeneous production demands in the pig slaughter sector. The cell-based process is designed to improve energy efficiency, sustainability, and increased productivity. The so-called "Meat Factory Cell" (MFC) is arranged in cells rather than lines, and disassembles the carcass from the outside-in. Contrary to current processes, the pig carcass is separated into seven constituent parts. The process begins with cut and removal of the four limbs, followed by separation of the belly and ribs from the saddle with the head intact. Detachment and extraction of the visceral organs from the saddle in one piece, completes the process.

In robotic automation, end of arm tooling (EoAT), also known as the end-effector (EF), is attached at the wrist, located at the distal end of the robot arm (Jing et al., 2018). EoAT is a crucial aspect of robotic technology. It refers to the equipment that interacts with parts and components. There are many different types of EoAT for robots, for example, sensors for detection or measurement (Vázquez-Arellano et al., 2016), a blade (Templar et al., 2002) and (Long et al., 2014), drill (Bi & Liang, 2011) or punch for cutting or material removal, a welding gun (Pires et al., 2003), riveter (Zeng et al., 2017) or hemming roller (Grosso et al., 2020; Templar et al., 2002) for joining materials. However, the task here is to review EoAT or EF used to grip, hold and manipulate the workpieces, primarily for the meat industry, but includes examples from other sectors.

The focus of this review is on slaughter processing and primal cuts of a pork carcass. The purpose of this literature survey is to explore the existing EoAT, unilateral gripping technology already available and suitable for use in the meat sector. In the cases where technology does not match meat industry requirements, the novel end of arm tooling (EoAT) with the potential for adaptation to support automation of the slaughter process is considered.

Review criteria focus on unilateral gripping technologies that are simple, cost-efficient, reliable, hygienic and safe to use without causing damage to the product. A suitable gripper should also have the capability to maintain sufficient theoretical holding forces, such as those set out in section 2.1, for various highly deformable meat pieces such as those from a pig meat slaughter process.

There are many forms of gripper available and still in development through research. Takacs et al. (2020)) reviewed the state-of-the-art robotic gripper designs, focusing mainly on shape locking and force-locking gripper types with the potential to use in the disassembly of red meat carcasses. However, in the review, unilateral, vacuum, or suction-based grippers did not feature. Yet, they offer potential for use in food and meat processing. In particular, vacuum grippers are simple, cost-effective and easily cleanable, with some flexibility to accommodate irregular surfaces depending on the design. Furthermore, they are non-destructive, avoiding the possibilities for pinching or puncturing that can occur with mechanical grippers. de Medeiros Esper et al., (2021) has critically reviewed current commercial and research-based meat processing automation systems that are either already used by the industry or have proven concepts. Reviewing the available information for these systems suggests vacuum suction systems are not readily employed. Instead, there seems to be a trend that leans towards hook and clamp style grippers and conveyor system combinations.

2. Understanding minimum gripper force requirements

This section presents a calculation of the theoretical holding force for a vacuum-based gripper system to give a benchmark value against which reviewed grippers can be assessed for their capability to grip and manoeuvre a given weight. The vacuum circuit is known to be complete when the air pressure between each cup and the workpiece is low compared to the atmospheric pressure (see description in 3.3). Furthermore, the criteria state that the gripper is for use within a meat abattoir setting. Thus, the heaviest primal pig meat cut weight is used to calculate the predicted required minimum force.

As discussed earlier (Alvseike et al., 2020) are developing a cell-based pig meat abattoir process resulting in seven primal-cut meat pieces. The saddle is the heaviest part of the pig at 37.4 kg and the shoulder is a lighter 9.8 kg, as indicated in Fig. 1 Fig. 1. For this exercise,

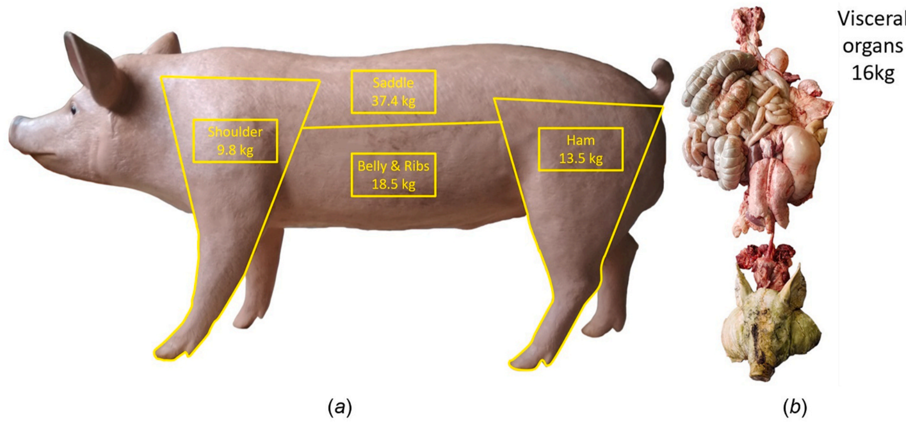

Fig. 1. Pig carcass showing primal pig meat cuts and associated weights (a) and visceral organs and associated weight (b). Image courtesy of Dmytro Romanov and Alex Mason, NMBU.

the saddle weight is selected as the mass variable in Equations (1), (3) and (4) to calculate the minimum theoretical holding force required by a unilateral gripper since it is the largest and heaviest part, providing the worst-case scenario. Furthermore, it is one of the cuts, along with the belly, that has a high probability of a vacuum forming due to its composition and structure.

2.1. Theoretical holding force of a vacuum suction cup

Within an automated vacuum gripping process, there is an importance placed on the suction cup's ability to handle the workpiece weight and acceleration forces. Therefore, the calculation of the theoretical holding force is completed for three different load cases.

- Load case 1: suction pad is horizontal, and force is vertical (see Fig. 2 (a) and Equation (1)).
- Load case 2: suction pad is horizontal, and force is horizontal (see Fig. 2 (b) and Equation (3)).
- Load case 3: suction pad is vertical, and force is vertical (see Fig. 2 (c) and Equation (4)).

Variables required to calculate the main force criteria (Schmaltz, 2021b) are as follows:

The coefficient of friction (μ) is the friction factor between the suction cup and the workpiece. Various theoretical guide values for heterogeneous surface conditions include oily and wet surfaces ranging between 0.1 and 0.3, with oily being 0.1. While wood, metal, glass and

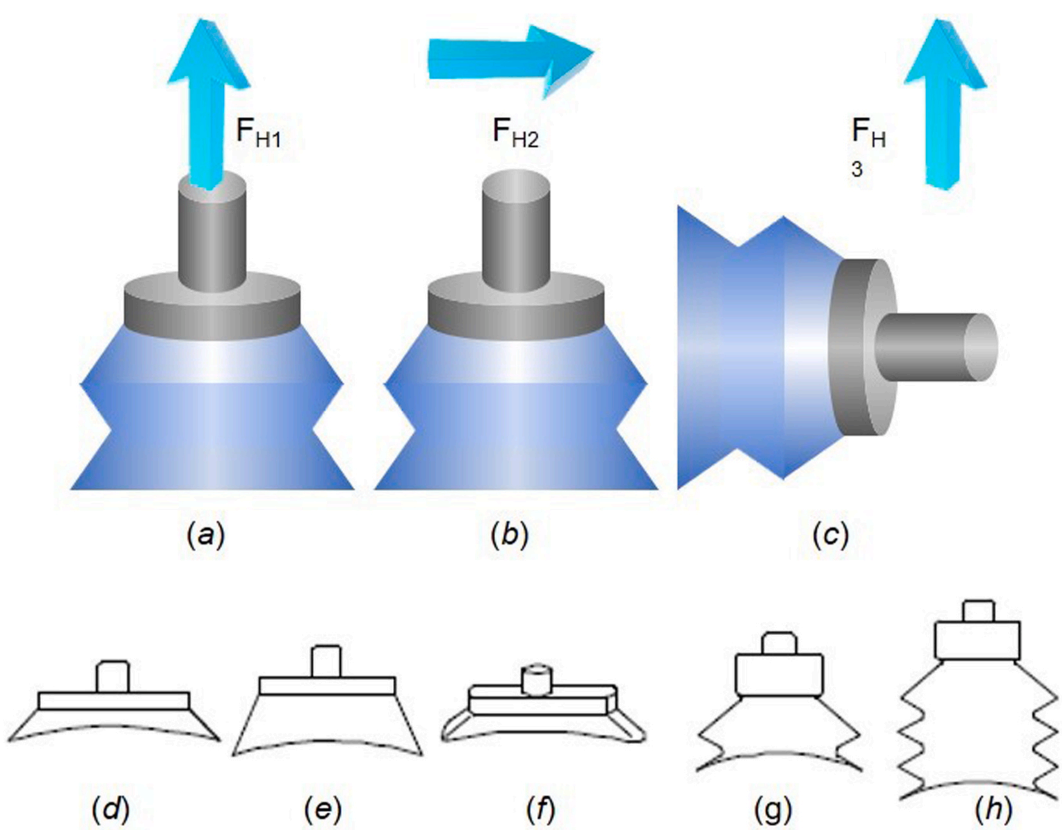

Fig. 2. First load case (a), second load case (b), third load case (c), and Different vacuum suction cup types - standard-flat and undulating surfaces (d), extra deep-round and deeply undulating surfaces (e), oval-narrow, oblong workpieces (f), bellows-inclined surfaces from 5° to 30° (g) & (h). Images (a–c) redrawn from "Basic Principles of Vacuum Technology", (Festo, 2021), and Images (d–h) reprinted rom (Festo, 2021). With permission from Festo Corporation, https://www.festo.com.

Table 1
Theoretical holding force (F_{TH}) and theoretical breakaway force per vacuum suction pad (FA)[a] results for all three load conditions at accelerations of; $a_e = 65$ m/s^2, $a_m = 35$ m/s^2, $a_p = 0.2$ m/s^2 and $a_e = 65$ m/s^2 at 50%, 25% and 10% robot acceleration capacities.

Force (N)	a = Acceleration (m/s^2)					
	$a_e = 65$	$a_m = 35$	$a_p = 0.2$	$a_e = 65$*0.5	$a_e = 65$*0.25	$a_e = 65$ * 0.1
F_{H1}	5596	3352	749	3165	1949	1220
F_{A1}	622	372	83	352	217	136
F_{H2}	8837	5097	759	734	4785	1544
F_{A2}	982	566	84	82	532	172
F_{H3}	9326	5586	1248	5275	3249	2033
F_{A3}	1036	621	139	586	361	226

[a] Theoretical breakaway force (F_A) is based on n = 9 suction cups in Equation (2).

stone have a coefficient of 0.5. For this exercise, the friction coefficient of choice is 0.6, which is that applied to rough surfaces.

A safety factor value must be incorporated into the calculations. Minimum safety factor value $S = 1.5$ and is dependent on surface condition of part, for examples in $F_{H1} – F_{H3}$ a safety factor value $S = 2$ is used.

The workpiece weight *(m)* = 34.7 kg and corresponds to the saddle which is the largest pig part as shown in Fig. 1.

Gravity $(g) = 9.81$ m/s^2

Acceleration *(a)* has variations depending upon the prefix as per Table 1, where *a*cceleration of Robot during E stop $(a_e) = 65$ m/s^2, acceleration of Robot during normal motion $(a_m) = 35$ m/s^2, acceleration of Robot programme $(a_p) = 0.2$ m/s^2 and acceleration of Robot during E stop @ 50% $(a_e*0.5) = 32.5$ (m/s)^2, 25% $(a_e*0.25) = 16.25$ (m/s)^2 and 10% $(a_e*0.10) = 6.5$ (m/s)^2

Equation (1) determines the theoretical holding force F_{H1} (see Fig. 2 (a)) for the first load case, in which the suction pad is horizontal with respect to the part and the direction of force is vertical.

$$F_{H1} = m \times (g + a) \times S \tag{1}$$

Equation (2) determines the theoretical breakaway force F_A (N) per suction cup, results in Table 2 based on $n = 9$ (Schmaltz, 2021b).

$$F_A = \frac{F_H}{n} \tag{2}$$

Equation (3) determines the theoretical holding force F_{H2} (N) (see Fig. 2 (b)) for the second load condition, in which the suction pad is horizontal with respect the part and the direction of force is horizontal (Schmaltz, 2021b).

$$F_{H2} = m \times \left(g + \frac{a}{\mu}\right) \times S \tag{3}$$

Equation (4) determines the theoretical holding force F_{H3} (N) (see Fig. 2 (c)) for the third load condition, in which the suction pad is vertical with respect to the part and the direction of force is vertical (Schmaltz, 2021b).

$$F_{H3} = \left(\frac{m}{\mu}\right) \times (g + a) \times S \tag{4}$$

2.2. Holding force requirements for grippers

Silicone is the material adopted for food industry suction cups. It conforms to both U.S. Food and Drug Administration standards for rubber articles intended for repeated use (Food and Drug Administration, 2020) and European Directives 80/590/EEC and 89/109/EEC on materials and articles intended to come into contact with food (Directives 80/590/EEC and 89/109/EEC of the European Parliament and of the Council, 2004). A bellows-type suction cup is best suited for gripping a workpiece with an uneven surface. However, in the interest of safety, the bellows-type cup does not meet the worst-case scenario of griping the saddle at an E-stop acceleration value of 65 m/s^2 for F_{A1} – F_{A3}. For example, the Festo VASB 125 mm diameter, silicone round bellows, 1.5 convolutions, has a holding force of 610 N at a nominal operating pressure of −0.7 bar (Festo, 2017). Table 1 shows the performance of this suction cup type is unsuitable for the worst-case scenario of F_{H3} = 93,626 N, which equates to a breakaway force of 1036 N per cup at an acceleration of 65 m/s^2 and based on a 9-cup configuration. It would take a minimum of 16 suction cups to hold the saddle at such high forces.

High forces calculated here mean standard suction cups of 200 mm diameter, with breakaway force (F_A) = 1610N could be used (Festo, 2021). The problem here is that the standard design suction cup does not function well on uneven surfaces. Thus, there is an inherent risk of some or all vacuum cup failure across different workpiece samples. See Fig. 2. (*d-h*) for different suction cup types.

Further options would be to reduce the robots operating acceleration capacity. Reducing capacity to 50% or maximum acceleration of 32.5 m/s^2 for E-stop yields a lower theoretical holding force (F_{H3} @ 50%) = 5275N or F_{A3} = 586N per cup. Working inside these parameters would allow the use of 9 x Silicone VASB 125 mm diameter, bellows, 1.5 convolution type suction cups with a breakaway force of 610 N per cup (Festo, 2017). Further reductions of acceleration, for example, down to 25%, would reduce forces such that only six cups are required or more cups retained for increased surface area coverage and security.

3. Unilateral gripping technologies

There are several unilateral gripping technologies available including, magnetic, needle, adhesive and air-based grippers. Magnetic gripping is possible when the surface of the object has strong magnetic properties such as Iron. In this case, depending upon the application, attachment via permanent magnets, electromagnets, or switchable magnets can be achieved (Tavakoli et al., 2015). However, magnetic grippers are dismissed since there is insufficient iron in pig meat to overcome the effects of gravity.

Penetrating grippers that use needles to skewer the working object, like the one developed by (Zoller et al., 1999) for the handling of non-rigid materials, such as polyurethane foams, are also not included for review as physical surface damage of the high-value food pieces occurs and contribute a risk of contamination.

Contiguity type gripping, discussed by (Monkman, 1995), requires the gripping surface to make direct contact with the object surface to create a holding force. The holding force in this type of gripper can be achieved by chemical adhesion, as used in the Permatack adhesive robot gripper. Another form of contiguity robot gripping uses thermal methods. In one such type, pre-impregnated Carbon fibre sheets with Thermo active resin adhesive (known as pre-preg) are subjected to localised heating, causing the resin to become viscous. Gripping is made possible by the tacky adhesive nature of the warmed resin. Gripper response time is limited by the time to heat and cool the Thermo active resin. The slow response time coupled with the oily texture of meat pieces would make adhesive type gripping strategies unsuitable whilst also posing a risk of contamination.

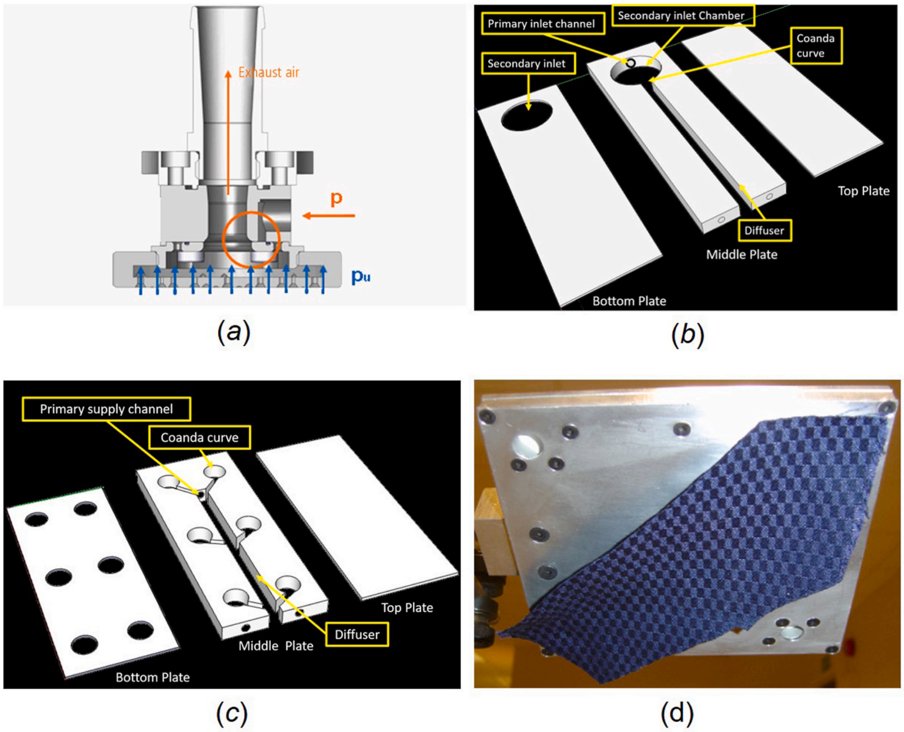

Fig. 3. Unilateral type gripping options Coanda effect (a) and parts for box style Coanda ejector-based gripper design 1 single suction head (b), design 2 multi suction head (c). Image (a) From "Operating principles of vacuum generation" (Schmaltz, 2021a), with permission from J. Schmalz GmbH, www.schmalz.com. Images(b-c) redrawn from "Experimental Study of Non-Contact Robot Gripper for Food Industries" (Elango et al., 2012), and (d) four ejector head Coanda gripper for textiles. Reprinted from CIRP Annals - Manufacturing Technology, 4 (1), T.K. Lien, P.G.G. Davis, "A novel gripper for limp materials based on lateral Coanda ejectors", 33¬36, (2008), with permission from Elsevier.

Of all the unilateral gripping technologies available, air-based grippers offer good options for the food and meat industries. Three such principles include Coanda, Bernoulli and Vacuum, and form the main subjects under review here.

3.1. Coanda effect

The Coanda effect presented in Fig. 3. *(a)* shows compressed air (P) guided through an annular gap (circled), accelerating the flow speed and creating the Coanda effect in which the exhaust air follows a convex surface. The air flowing along the convex surface causes a suction (Pu) in the ambient air (Schmaltz, 2021a).

A vacuum-based gripper capable of holding objects of various structures has been used in the food (Elango et al., 2012), (Natarajan et al., 2018) and textile industries (Lien & Davis, 2008). (Elango et al., 2012) developed a vacuum gripper capable of handling an assortment of materials. The material compositions include uneven surfaces, texture variability and non-uniform shaped bodies. The gripper designs consist of two box style, Coanda ejectors and are said to comply with food hygiene standards. Design 1 depicted in Fig. 3. *(b)*, is a single suction head, while design 2 is a multi (six) suction head and shown in Fig. 3 *(c)*. At a vacuum pressure of 1200 N/m^2, the single vacuum ejector registered a lift force of ca. 1.5 N. In contrast, the multi vacuum gripper has a reduced lift force of about 0.25 N for an equivalent value vacuum pressure.

Experimental observations showed that the single vacuum design could lift various objects such as apples, oranges, tomatoes, garden eggs and plums due to the increased lifting force. Design 2, with its lower lift force, rendered it only capable of lifting objects consisting of a flat surface. Further to this, the experiments proved that no damage occurred to fruit skin after being gripped.

This work was built upon when (Natarajan et al., 2018) designed a box style, 3D printed Coanda ejector and conducted simulation in SolidWorks Flow to understand the design properties. Physical tests proved the grippers ability to grip and lift apples, oranges, tennis balls and a flat aluminium bar. The items weighed between 58 g and 123 g, with the aluminium bar being picked most effectively due to its flat, smooth surface. The maximum gap between the gripper and aluminium bar that allows a successful pick increases as a function of increased air pressure. The minimum gap length between the ejector and spherical object is zero as the picked object must cover the secondary inlet completely for gripping to occur. No indentation marks were visible on the oranges or apples.

(Lien & Davis, 2008) have proposed a universal gripper design to overcome challenges in the textile industry due to textural differences, permeability variance and size constraints imposed by the shelf systems used for storage. The literature shows that gripping via clamping, needles and freezing are all suitable technologies, but are dependent on the subject material. For example, the needle type gripping of smooth leather would inherently mark and damage the product surface, whilst clamping can crush delicate fibres and vacuum can stretch and distort some fabrics.

A reduced-size planar Coanda ejector developed for gripping within the tight confines of shelf storage systems demonstrated its suitability for gripping rough and smooth leather and more porous materials. Fig. 3 *(d)* shows that the ejector can be built with independent multi-suction heads, creating a sufficient lifting force for textiles over a wide surface area. Lien & Davis, (2008) have stated that it is also suitable for food handling with sufficient suction force for lifting fish filets and meat slices for example.

3.2. Bernoulli effect

Fig. 4. *(a)* shows how Bernoulli's principle is employed to create a vacuum gripper. Compressed air escapes and accelerates through holes in the suction cup. The result is the static air pressure reduces and creates a vacuum at (A). The accelerated air escapes to the sides shown at (B) and creates a cushion of air between the workpiece and the pad. A high flow rate compensates for leakage and facilitates a method to handle porous workpieces with minimal or no contact (Schmaltz, 2021a).

Bernoulli grippers are non-contact vacuum grippers that produce an air cushion between the gripper and the workpiece. Although they are known for generating low gripping forces, they are also known for being

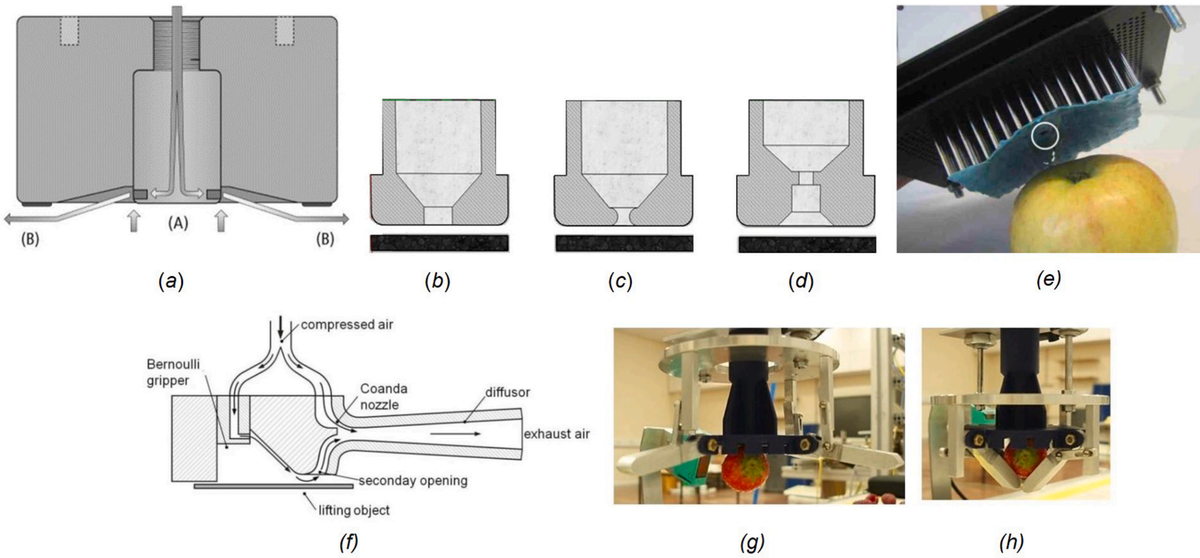

Fig. 4. Unilateral gripping options Bernoulli effect (a)from "Operating principles of vacuum generation" (Schmaltz, 2021a), with permission from J. Schmalz GmbH, www.schmalz.com, three different nozzle forms (b) rounded, (c) radial & (d) stepped images(b-d) redrawn from (Pavlo Maruschak et al., 2019). Hybrid Bernoulli gripper with deformable 3D surface (e). Reprinted from Industrial Robot: An International Journal, 37 (6), Petterson, A., Ohlsson, T., Caldwell, D. G., Davis, S., Gray, J. O., & Dodd, T. J., "A Bernoulli principle gripper for handling of planar and 3D (food) products", 518¬526, (2010), with permission from "© Emerald Publishing Limited all rights reserved." Combined Bernoulli gripper with Coanda based exhaust system (f). Reprinted from Procedia CIRP, "A Novel Gripper for Battery Electrodes based on the Bernoulli-principle with Integrated Exhaust Air Compensation", 4, Kai Stühm, Alexander Tornow, Jan Schmitt, Leonard Grunau, Franz Dietrich, Klaus Dröder, (2014), with permission from Elsevier. Bernoulli hybrid design that incorporates four mechanical fingers to aid the picking of non-flat food items (g–h). Reprinted from Proceedings of the 9th WSEAS International Conference on Signal Processing, Robotics and Automation (ISPRA′10)", Design and feasibility tests of flexible gripper for handling variable shape of food products", Rosidah Sam & Samia Nefti, (2010), 329–335, with permission from Sammi.

reliable, durable, and capable of lifting porous objects. Savkiv et al. (2017) provide a comprehensive description of the Bernoulli gripper operating principle, beginning with a principal component description. The authors also present a mathematical analysis of 5 alternative designs and an assessment of their design functions. The functions assessed include lift capacity, the maximum gripping distance, and the working value of radial clearance.

(Pavlo Maruschak et al., 2019) have carried out analysis of influence of three nozzle forms including rounded, radial, and stepped (Fig. 4. *(b-d)* respectively). Results show that when using the radial or stepped nozzles with a tapered construction lifting capacity of the Bernoulli gripping devices can be increased by 26%.

As previously mentioned, Bernoulli grippers are known for non-contact lifting of planar, textile or, porous sheets. However (Petterson et al., 2010), have designed a novel Bernoulli gripper with a twist. Their design has incorporated a deformable surface that the gripper can press against a 3D object, for example an apple, forming the gripper to its shape. The deformable surface is based on a matrix pin board, includes 16 rows and 21 columns of pins as shown in Fig. 4. *(e)*. The pin surface is covered with a 1.5 mm thin latex rubber sheet and bonded to each pin creating a continuous surface. Results of lift force tests show a 65% increase for this design compared to a 2D Bernoulli gripper.

(Stühm et al., 2014) developed a novel Bernoulli gripper for use in an automotive battery assembly clean room. The Bernoulli principle by design blows its exhaust air into the environment, as depicted in Fig. 4. *(f)* and can have detrimental consequences within cleanrooms due to the emission of micro-particles into the atmosphere. To improve cleanroom air quality, the authors designed a Bernoulli gripper inclusive of Coanda ejector as an exhaust mechanism for the grippers spent airflow. The design is efficient in that only a single air source is required to drive both the Bernoulli gripper and Coanda exhaust. Early tests show the potential to reduce particle contamination. Such a device could also be a working answer to improving hygiene in the food industry where Bernoulli type grippers are employed by reducing possible contamination from particles of food, meat or blood, for example, from being ejected into the ambient air.

Sam and Nefti (2010) present another Bernoulli hybrid design that incorporates four mechanical fingers to aid the picking of non-flat food items, such as strawberries. First the Bernoulli gripper lifts the workpiece Fig. 4. *(g)*, and when grasped, all four mechanical fingers are raised below the work piece to secure it Fig. 4. *(h)*. Their design is also said to reduce running costs since the Bernoulli principle is such that it requires a constant flow of air. The compressed air flow has a purity level equivalent to ISO 85735.1 Class 2.2.1 because of its use in contact with food. The perceived cost reduction is a result of the reduction of required airflow when the fingers are in place.

3.3. Vacuum grippers

In its most basic form, simply pushing a suction cup against a surface can create a vacuum gripper as the push action on the suction cup forces the air inside to be expelled, reducing the internal air pressure to less than that of atmospheric pressure (Health and Safety Executive, 1998). The resultant pressure differential causes a vacuum to form between the workpiece and the suction cup. Alternatively, the under-pressure vacuum is formed using a pump or a flow generator such as a Venturi ejector (Tuleja et al., 2013) to expel the air between the part and the suction cup.

Fig. 5. *(a)* shows the Venturi principle of operation. The introduction of compressed air to the ejector at (A) and into the motive nozzle (B) with a reduced cross-section increases the compressed air acceleration, increases dynamic pressure and reduces static air pressure. Vacuum generation forms as the accelerated air travels beyond the motive nozzle and is drawn into the vacuum ejector via the vacuum connector (D). The compressed air and the sucked in air escape the ejector through the silencer (C) (Schmaltz, 2021a).

Vacuum grippers have been combined with other gripper types to overcome challenges picking or grasping different food types

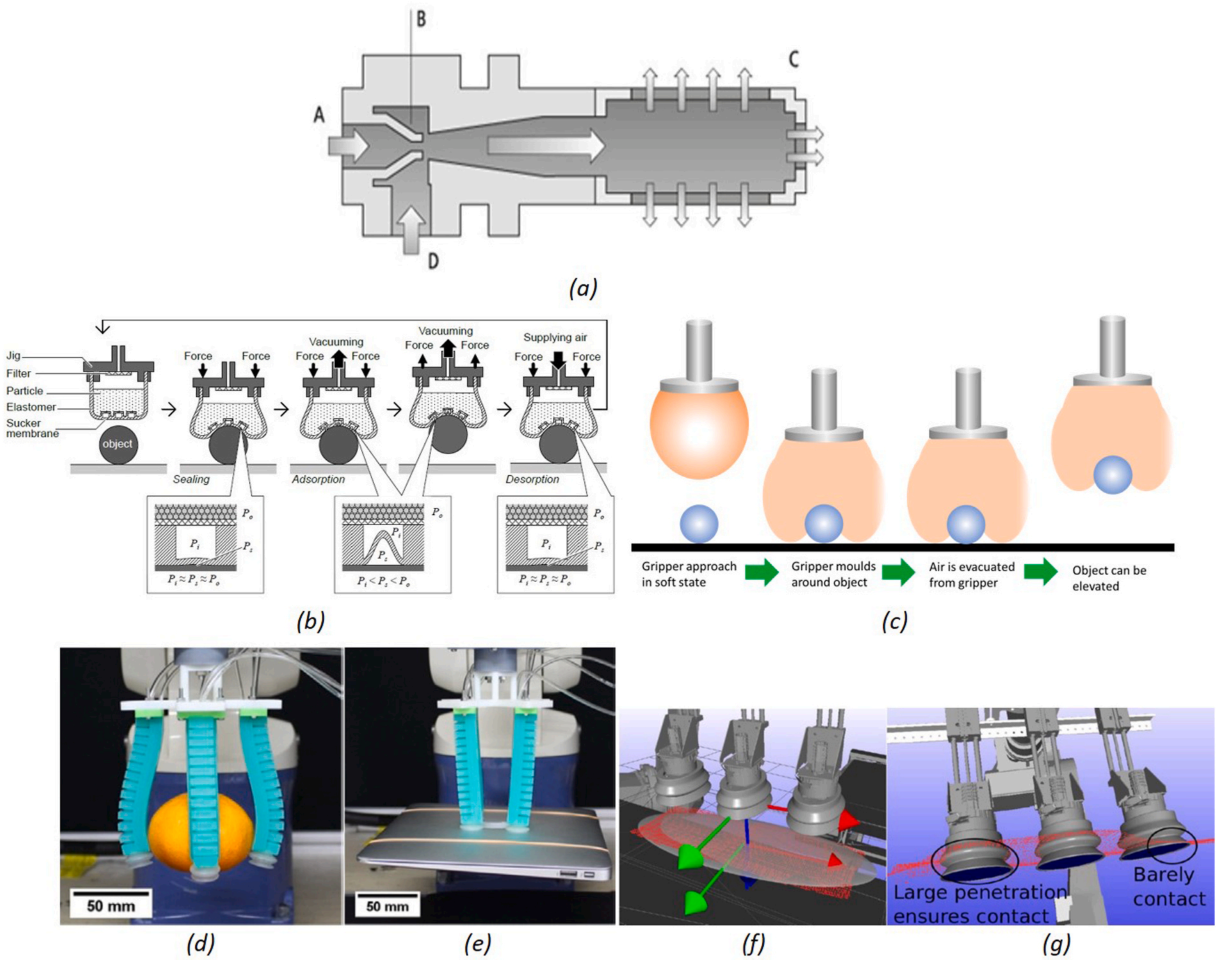

Fig. 5. Unilateral gripping options, vacuum based on Venturi ejector (a) (Schmaltz, 2021a) with permission from J. Schmalz GmbH, www.schmalz.comprinciple of a proposed vacuum gripper imitated octopus (b), © [2015] IEEE. Reprinted, with permission, from [IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Hamburg],., universal robot gripper based on the jamming of granular material (c) redrawn from (Brown et al., 2010)., (Tomokazu et al., 2015), dual mode soft gripper - soft finger gripping of an orange, (d) and suction pads on the end of the soft fingers grip and lift a laptop (e), (d–e) reprinted from Robotics and autonomous systems, 125, "A dual-mode soft gripper for food packaging ", 1¬9, (2020), with permission from Elsevier., vacuum suction cup array - air cylinders act like spring dampers adjusting height of suction cups with respect to meat height to ensure vacuum circuit - flat grasp. (f) PCA analysis is used to determine the grasp frame based on the red point cloud. The ellipsoid illustrates the Eigenvectors and Eigenvalues of the PCA analysis, (g) the final grasp frame is determined to ensure the suction cups move through all points, even for highly uneven surfaces. The actual final frame is moved 40 mm further down to make the contact more reliable in practice, (f–g) reprinted from Proceedings of the 2018 4th International Conference on Mechatronics and Robotics Engineering (Jørgensen, Krüger, et al., 2019), with permission from ACM, Inc. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

(Tomokazu et al., 2015), (Wang et al., 2020) & (Curhan et al., 2019).

(Tomokazu et al., 2015) have developed a gripper combining a novel vacuum gripper with a phase-change utilization type gripper, capable of gripping flat, curved, uneven and grooved surfaces. The vacuum part consists of suckers designed to mimic the suckers on an octopus's tentacle as shown in Fig. 5. *(b)*. Higher lifting success rates are achieved to uneven and curved surfaces when liquid membranes, including water and oil, were added to the part. Furthermore, lifting forces were also increased by a factor of 1.8 when the oil membrane was applied. However, there were unwanted effects associated with oil use as it lessens the friction acting between the gripper and workpiece, which allows the part to become easily separated due to slippage.

The phase change utilization part is similar in concept to the jamming-based gripper developed by (Brown et al., 2010). This gripper design consists of a single nonporous plastic bag filled with granular matter. Fig. 5. *(c)* shows the gripper first lowered down towards the target. On contact with the target, the gripper deforms around the object. The pump is then activated to evacuate the gripper of air, rendering the granular material rigid and forming the grasp. Finally, the grasped object is lifted vertically from the surface. When the required actions are complete, the air is pumped back into the bag to release the grippers hold.

In contrast (Wang et al., 2020), developed a combined Soft Robotics dual mode gripper consisting of four fingers and based on the PneuNets actuator. The difference here was the positioning of vacuum cups fitted to the distal ends of the fingers. Finger gripping via friction is due to inflation and deflation of the fingers arranged perpendicular to each other. Deflation of the fingers reduces air pressure and increases the opening distance whereas, increasing the pressure reduces the opening distance to form a grip around the target object and capable of lifting objects, such as eggs, oranges, and chicken pieces. Vacuum cups at the end of the fingers allows the gripping of plate-like objects such as laptop computers or elongated items such as sausages. Fig. 5. *(d)* shows gripping of and orange using fingers and Fig. 5. *(e)* gripping of a laptop using suction respectively.

(Curhan et al., 2019) invented a rectangular, planar vacuum plate consisting of multiple small vacuum holes assisted by six soft robotic fingers. The vacuum plate initially lifts the product, and the pneumatic soft robotic fingers gently grasp the edges to lift securely and without damaging or deforming the product, specifically burger patties. The small multiple suction holes replace the vacuum cup to reduce the probability of patty deformation, and chunks of ground meat, from being sucked into the vacuum. The vacuum hole diameters are said to be between 1.0 and 3.0 mm, depending on application. The gripper is believed to be suitable for a range of food products and not limited to meat, fish, or poultry pieces but may also encompass other fragile and flexible food types such as dough and jelly.

(Dickerson et al., 2005, pp. 214–219) developed an automated case packing robot for picking Styrofoam trays of pork and placing them into a tote before shipment. The system did not consist of a robot arm, as such, but of a gantry and rail system capable of moving a vacuum base end effector in x, y and z directions. The end effector was a vacuum gripper made up of 3 lines of vacuum suction cups. The outer most lines run parallel with three cups evenly spaced either side, while the middle line consisted of only 2 cups that are not adjacent to, but diagonal to the outer cups. During field tests the system packed nearly 1 million trays with an average packing rate of 1.27 s. Moreover, the vacuum gripper successfully grasped 99.64% of the trays.

(Stommel et al., 2014) discuss the difficulties of sorting animal offal, particularly from lamb carcasses in New Zealand and Australia, where yields of only 70–91% for high-value offal including heart, liver and kidneys are recoverable due to labour shortages. They generate a hypothesis for the sorting and independent removal of single lamb offal pieces from the collection of internal organs, based on the extensive literature review of previous research. The hypothesised solution incorporates a soft peristaltic table to gently sort the organs into a more favourable position for identification and retrieval. In this solution, a dual-arm robot uses one arm to grasp and lift the targeted organ. Whilst the other arm is fixed with a cutting tool to detach any connecting tissue before the gripping arm moves the part to its next destination. Of interest here is the technology proposed for vacuum gripper.

Stock (2021) reports in a news article on a new robot and flexible conveyor system called ‘Stretch’ developed by robotics company Boston Dynamics. The system development followed industry requests to the company to find a solution to ease the unloading warehouse delivery trucks. The robot comes equipped advanced sensing and computer vision system and a gripper system consisting of a square array of nine vacuum suction pads capable of lifting various boxes and shrink-wrapped cases with a payload of up to 23 Kg and a rate of up to 800 packages per hour.

(Jørgensen et al., 2018), (Jørgensen, Krüger, et al., 2019) & (Jørgensen, Bo, et al., 2019) show vacuum gripping of raw meat cuts is far more challenging than that of the uniform packaging discussed in (Dickerson et al., 2005, pp. 214–219). The Danish consortium (Jørgensen et al., 2018) present the development of a fully automated robot arm with six degrees of freedom (6DOF) and a suction-based vacuum gripper to overcome challenges lifting and placing individual pork bellies onto a moving conveyor as depicted in Fig. 5. *(f)*. Pork belly structure includes three layers consisting of skin, fat and muscle with little or no bone combining to form a sheet of uneven height along its length and breadth. Its composition is highly deformable with a greasy texture making vacuum suction for gripping problematic to achieve.

The deformable nature can lead to ripples in the skin such that a complete vacuum circuit can often fail to be made. The deformability factor can also lead to a negative secondary vacuum forming with the surface beneath the target pork belly. This results with a grasp including more than one piece of pork belly or the tray in which the bellies sit. This additional vacuum will result in the vacuum failing or an incorrect process downstream, i.e., multiple pork bellies being picked and placed one atop the other on the conveyor.

The vacuum gripper design as shown in (Jørgensen et al., 2018), (Jørgensen, Krüger, et al., 2019) & (Jørgensen, Bo, et al., 2019) incorporates three suction cups with an elliptical suction area of 110 mm × 150 mm and fitted to a rod so that the distance between could be adjustable. Following trials, the cups best placement is at an equidistant spacing of 150 mm apart. The height variation of the belly pieces could result in vacuum failure due to the inability of a vacuum suction pad and the pork belly to make contact. The issue is solved by attaching air cylinders to the vacuum cups to act as spring dampers with a 100 mm stroke and sufficient air pressure that provides stiffness to the springs and allows the suction cups to be pushed towards the surface to form the vacuum as shown in Fig. 5. *(g)*.

Two alternative strategies for gripping and transporting the meat from box to conveyor were developed, both of which relied on a certain degree of artificial intelligence, utilising a segmented point cloud of the meat surface to determine the grasp motion. Generation of the point cloud is via a 3D vision system employing two high-definition (HD) cameras and a light projector to create a structured light approach. Here (Jørgensen, Bo, et al., 2019), the complete system is presented in-depth and is beyond the scope of this document since the intention is to conduct a review of unilateral-based grippers.

Firstly, the "flat grasp" employs Principal Component Analysis (PCA) of the point cloud to determine a frame. The PCA frame and a suction cup simulation is combined to perform a distance calculation between the suction cup and the meat. The grasping tool is lowered 40 mm beyond the bellies z height, after which activation of the suction cups ensure a complete vacuum circuit is activated. The meat piece can then be lifted and placed on the conveyor.

Secondly, the "rolling grasp" uses the spring damper to generate a grasping strategy that eliminates the negative secondary vacuum effect. In this strategy, the point cloud analysis allows the suction cup placement towards the edge of the meat piece, using the PCL concave hull algorithm, maintaining it within the meat boundary to ensure the vacuum circuit is complete. Once the vacuum is engaged, the vacuum cups and the meat are lifted in a rolling motion, taking advantage of the spring dampened suction cups. This controlled motion minimises the amount of pork meat able to lift before air can flow beneath the belly and negate the secondary vacuum.

The grippers ability to grasp different pork cuts, including pork bellies with and without skin, pork loins and pork back, is proven with varying degrees of success. Classification of the grasping was stated as (S) success, (FL) failure due to vacuum loss during lift, (FM) failure due to vacuum loss during motion towards the conveyor and (FML) failure due to the meat piece sticking to the meat piece or the box below it, causing multiple object lifts during the grasp. The flat grasp strategy performed the worst when concerned with achieving a proper grip during the initial grip and lift, with FL and FML failure rates of 23% and 5.8%, respectively. It is also the only strategy that was lifting two meat pieces at once, failing more often at the beginning of the lift. The rolling grasp on pork bellies with skin was the most effective combination with a 0.0% failure rate for grasping and lifting (Jørgensen, Krüger, et al., 2019).

4. Discussion

This section discusses the suitability, of the reviewed gripper technologies, for use within a red meat automated robot abattoir cell. The discussion is supported by Table 2, highlighting the advantages and disadvantages of the most relevant gripper technologies.

Table 2
Comparison of gripping strategies with regards to potential use in red meat slaughter processes.

Technology	Load	Maintenance	Hygiene	Damage	Comments
Bernoulli	-	+++	++	++	Unlikely to meet payload demands, high vacuum and low flow rate = high energy costs due to air consumption, hybrid designs increase complexity and cost.
Coanda	-	+++	++	++	Unlikely to meet payload demands. Similar to Bernoulli.
Vacuum Pump	+++	+	++	+++	High initial investment, increased maintenance and running costs.
VESS	+++	+++	+++	+++	High vacuum and low flow rate, reduced energy costs, low air consumption and low pressure, low maintenance - unlikely to contaminate airflow with part debris due to straight through design.
VEMS	+++	+++	+++	+++	Similar to VESS - fast evacuation time – but slightly slower than VESS.
Curhan et al. (2019)	+	+	+	+++	Small hole blockage potential, unlikely to meet payload demands.
Wang et al. (2020)	-	+	+	++	Unlikely to meet payload demand, finger grip of non-flat objects relies on friction between balloon like fingers and part, only three fingers with vacuum ends – insufficient force.
Tomokazu et al. (2015)	-	+++	++	++	Unlikely to meet payload demand-but potential to upscale, requires liquid membrane between part and gripper for optimum grip force so not hygienic.
Brown et al. (2010)	-	+++	++	++	Unlikely to meet payload demands, not suitable for flat like structures.
Dickerson et al. (2005)	++	+	+++	+++	Vacuum pump issues, only used to move boxes, not 6-axis of movement, has potential with adaptions like all vacuum and ejector systems
(Mathew Stock, 2021)	+++	+	+++	+++	Mobile gripper robot, vehicle mounted, capable of lifting 23 kg boxes in restricted space, but requires power link or recharge time leading to increased maintenance.
(Jørgensen et al., 2018, 2019; 2019a)	+++	+++	+++	+++	Best solution, can be scaled up to meet payload demand, use of spring dampers ensure good grip and lift of uneven surfaces, demonstrated gripping and manipulation of pig belly meat pieces

(VESS = Vacuum ejector single stage), (VEMS = Vacuum ejector multi-stage), (Curhan – Jørgensen reference individual vacuum grippers), +++ = high impact, ++ = impact, + limited impact, - = negligible impact.

The research by (Natarajan et al., 2018) raised the question, could the use of an array of independently controlled vacuum suction heads increase the overall lift forces? Based on the theoretical holding force calculations made in section 2.1 and the subsequent discussion in 2.2, for load case 3 and the robot system running at 25% capacity, the calculated theoretical holding force of 3249 N would require 2166 independently controlled vacuum ejector heads with 1.5N lift force to compensate. Therefore, such a system is impractical.

Regarding Coanda ejectors for handling food, more testing could have been conducted, on irregularly shaped foods, including food types such as sliced ham cheeses etc., such testing would have proven if the vacuum gripper can cause damage across a range of different food items. It would have also verified its suitability as a universal gripper capable of handling various food items of different shapes, textures, and fragility. Also, it is unclear if the lifting force of larger workpieces could be improved using multiple independently controlled vacuum suction heads. However, in its current form, it is more suited to picking flat smooth objects of relatively low payload limits. Hence, Coanda ejector type gripper designs are considered unsuitable for the primal meat cut processes for this reason.

Bernoulli type grippers have shown novel non-contact gripping of many types of food, textiles and electronic components. Furthermore, the generation of increased lift forces via nozzle optimisation and hybrid designs is proven (Maruschak et al., 2019). One such hybrid has also shown direction towards improved environmental impacts that could transfer seamlessly to the food industry, improving hygiene (Sam and Nefti, 2010). Unfortunately, as with Coanda ejectors, Bernoulli ejectors do not generate sufficient forces to be considered for the red meat slaughterhouse environment and are therefore disregarded.

Some of the grippers that combine vacuum with alternative technologies for gripping, which we review here, are not suitable as they lack the robustness and holding forces required for a pig slaughter process, at least in their current forms. The soft pneumatic finger types, similar to a balloon, rely on inflation and are limited in both rigidity and angular movement for wrapping. Their reliance on friction and lack of stiffness would probably cause them to fail, considering the greasy texture and high loads imposed by individual primal cut pig meat parts.

The octopus-sucker-based design was suitable for light loads, but maybe there is scope to upscale. However, the literature (Tomokazu et al., 2015) shows that a liquid oil membrane is needed at the interface between the part and the vacuum pad to improve vacuum formation. Thus, it would not be suitable for the meat industry.

The vacuum gripper, peristaltic table concept for removal of individual visceral organs (Stommel et al., 2014) is an interesting idea. However, it is beyond the scope of red meat slaughterhouse processes, concerned with only primary cuts, including visceral organs and pluck removal from the carcass as one unit (Alvseike et al., 2020). Furthermore, there is a greater risk of contamination from individual organ removal and the prospect of unwelcome, increased process cycle time.

However, the concept of dual gripping technologies is an intriguing idea. For instance, in our research concerning abattoir automation (Alvseike et al., 2018), a mechatronic based dual-finger gripper to hold and manipulate meat parts while they are cut and removed from the carcass is employed. The manipulation of the meat during the robot cutting process can result in damage imparted to the high-value meat-part, due to significant torsional forces acting on the meat part at the gripper holding point. The question is then, is there scope to develop a combination gripper, for example, by adding a low-cost, lightweight vacuum extension to the mechanical gripper to alleviate torsion forces during the manipulation process?

Of the two purely vacuum-based gripping systems reviewed, the first (Dickerson et al., 2005, pp. 214–219) was concerned with lifting and transporting packaged meat to a conveyor belt. Although the system is successful at gripping and moving Styrofoam packets of pork meat, the system lacks the sophistication required to conduct the required tasks of an automated slaughterhouse, due to its lack of agile mobility. Unfortunately, the basis for its success is its ability to pick and place consistently uniform Styrofoam packages and unclear then if this success would translate to the raw meat cuts produced by an abattoir process.

The mobile robot unit developed for unpacking warehouse delivery trucks by Boston Dynamics (Stock, 2021) has the agility to work and manoeuvre within tight confines and has a vacuum gripper capable of lifting 23 kg packages. Its manoeuvrability could eliminate potential robot arm reach limits and collisions that could be encountered in static robot systems. However, it is not clear if making the suction cup array larger will increase the maximum lifting force, if it is restricted by the robots' maximum payload limit and vehicle centre of gravity, or that it would be suitable for lifting raw meat pieces. Furthermore, the robot battery operated vehicle would require additional maintenance and down time in the form of battery charging.

The final vacuum-based system by (Jørgensen et al., 2018), (Jørgensen, Krüger, et al., 2019) & (Jørgensen, Bo, et al., 2019) is of the most interest. Their system picks pork bellies from a box and places them on a conveyor. This system poses the most curiosity because of its use for lifting raw cuts of pork belly meat pieces. Its novelty is the addition of air cylinders attached to the vacuum cups that act similarly to spring dampers. The air cylinders allow so-called “rolling grasp strategies” to be performed and increase the success rate of complete vacuum circuits across height varying and deformable pork belly pieces.

The risk of blockages caused by debris sucked into the vacuum system was raised by (Curhan et al., 2019). Their hybrid gripper design consisted of a plate with many small vacuum holes combined with gripper fingers for gripping and lifting meat patties to give one part example.

The holes were small enough to negate the possibility of meat pieces being sucked into the vacuum system and cause blockages that would result in increased maintenance. In contrast, a red meat abattoir process would require gripping, lifting and placing large, skin-covered meat pieces. As a result, there will probably be no such blockages within the vacuum system.

However, it could be possible for small debris from cuts, including skin, meat, bone, blood or, grease to be a risk to the vacuum system. In this case, the use of single stage vacuum ejectors is unlikely to contaminate airflow with debris due to their venturi design principle. As discussed earlier, the compressed air and the sucked in air evacuate through the silencer along with any debris. The authors experience with venturi ejector design is that the silencer filters are inadequate and require design modifications. Furthermore, the work conducted by (Jørgensen et al., 2018; 2019; 2019a) is primarily concerned with the gripping of pork belly pieces from a box and placing the said belly pieces onto a production line. In this work they were able to pick meat both with and without skin. Although it was most successful with the vacuum in contact with the skin, there is no record of maintenance issues caused by debris entering the vacuum system in either of the three articles.

5. Conclusion

Labour shortages within the meat industry due to recruitment difficulties and absenteeism through sickness, injury or the spread of Covid-19 coupled to the expected 12% growth in meat consumption over the next decade are major driving factors for slaughterhouse automation. However, a traditional slaughterhouse setup consisting of a disassembly line of many discreet processes requires significant investment but offers low flexibility and reliability. Such prohibitions exclude small volume markets, such as those in rural Norway with long transport distances from investment in automated systems.

Automation of the slaughter process would relieve labour shortages, improve working conditions, reduce contamination and infection, and lead to productivity and profitability increases for the red meat industry. For this to be true for small market abattoirs, changes to the general set up and process are first required to deliver cost-effective and flexible solutions. Aside from this simple, low-cost and reliable tooling that conforms to safety and hygiene standards without damaging the product is needed to support reduced cost automation solutions.

This paper reviews unilateral gripping solutions, not limited to the food or meat industries, for use, as-is, or suitable for adaption for use in support of an automated slaughterhouse environment.

Calculations show the theoretical holding and breakaway forces required for a hypothetical vacuum gripping system. The basis of the formula considers the expected maximum payloads found in a new concept for the pig meat slaughter process (Alvseike et al., 2018) & (Alvseike et al., 2020), and provide a benchmark to gauge the suitability of the grippers reviewed in this paper.

Unilateral gripping devices such as magnetic, needle and adhesive gripers were immediately disregarded as ineffective, damaging to the product or unhygienic. Suction type grippers based on Coanda and Bernoulli principles, including hybrid designs incorporating novel additions, have also been discounted due to low holding forces that are insufficient for the heavier payloads expected within a primal red meat cutting environment.

Simple vacuum-based grippers have proven to offer the best solution and warrant further investigation. Especially when combined with novel additions such as air cylinders that act like spring dampers to overcome part variance as described in (Jørgensen et al., 2018), (Jørgensen, Krüger, et al., 2019), (Jørgensen, Bo, et al., 2019). However, even with such adaptations to vacuum gripping systems, forming and sustaining a vacuum circuit for gripping and manipulation of larger, highly deformable and structurally variant meat pieces are yet to be proven in a real-world scenario. Thus, future work centring on designing adaptions of vacuum gripping systems and conducting physical experiments to attest or refute concept suitability for future red meat slaughter processes is essential.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.tifs.2021.12.017.

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