RoBUTCHER

D5.1
Gripping State-of-the-Art Review

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Abstract:	Applying pulling force is essential in various stages of the pig processing, e.g., when dissecting the limbs or removing the inner organs. Various gripping solutions exist, which may allow for the grasping and gripping of soft tissue organs ranging from skin to bowels. An overview of existing commercial, patented and prototyped version is provided to be able to compare the layout and capabilities of different gripping solutions.
Keywords:	Soft tissue gripping; robotic grasping; smart gripper

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Disclaimer

Executive Summary

This document presents a systematic review about the state-of-the-art robotic soft-tissue gripping solutions in the food-industry focusing on meat-grippers. The purpose of this deliverable is to provide a categorized analysis about the currently used grippers that could be used or adapted to the grasping tasks in the RoBUTCHER project.

The paper is intended to help the gripper-development tasks in WP5, thus it discusses the soft-tissue grippers recently published in scientific papers and the relevant patents too. The purpose of the review of scientific papers was mainly to provide high-tech or out-of-the-box ideas, while the patent research was expected to deliver complete, commercially available solutions.

The deliverable provides potentially applicable soft-tissue gripping principles, description of gripper-patents and technical specifications of published state-of-the-art grippers in an appendix. A suitable, commercially available gripper that could carry out the organ- and the limb gripping too was not found. However, a gripper produced by DTI-DMRI is already proven capable of the latter, and potentially applicable ideas were revealed and discussed.

Abbreviations and Acronyms

Notes on Abbreviations

CHU	Carcass handling unit
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
TRL	Technology readiness level
EC	European Commission
DOF	Degrees of freedom

Contents

1. Introduction

1.1. Specification of the problem

Grasping and gripping are typical tasks in any robotic application, especially where physical interaction is required. Meat processing is a very labour-intensive process, where two major task domains of grasping have been identified within the frame of the RoBUTCHER project:

1) Grasping the limbs to facilitate cutting of the legs;
2) Grasping inner organs, primarily the trachea to facilitate the cleaning of the abdomen from the organs.

Gripping and handling procedures start with identification of the point/vector of interest for the gripping. The point is often an anatomical landmark on the carcass or organ. This requires that the tissue characteristics to be grabbed are known. Added to this, the target objects are not fixed in space.

Furthermore, there will be two more grasping tasks that will be covered later in the RoBUTCHER project:Grasping, lifting and placing the saddle of the carcass (including the head);

4) Grasping, lifting and placing the emptied abdomen of the carcass.

The grasping tasks 1) and 2) should be a focus of the project and dealt with separately from 3) and 4), since the latter two are almost traditional pick-and-place tasks with fundamentally different and less challenging difficulties:

- The target objects are fixed.
  - There are known points on the objects, the CHU fixation points.
  - A 3D scan can be performed just before grasping, resulting in a point-cloud of the whole target object.
- Both parts will be removed at the end of the process (after all cuts and gutting); these actions should not influence or interact with any other process.
- There is no danger of damaging adjacent tissues resulting in contamination.
- The body-parts in question can even be pierced through at the right points (e.g. using a hook), thus slipping should not be a concern. While this is not a preferred option, it is quite standard practise in the industry today.
- The challenge here is the weight of these parts, primarily the saddle (with head) being around 33 kg, while the abdomen (similarly to the organs altogether) around 15 kg[1].

1.2. Grasping the limbs

The grasping of limbs fulfils two main purposes: supporting the limb during the cutting procedure and removing the limb from the carcass after completion of the cutting. The purposes are shown in Figure 1 and Figure 2, which illustrate grasping the shoulder and the ham respectively. The shoulder needs to be supported and lifted away from the carcass, as the cutting trajectory is quite accessible without the need for separating joints.

The grasping of the ham is more delicate as the support also makes the way for access to a cutting trajectory by stretching the leg downwards to expose the joint between hipbone and the femoral head. Figure 3 shows the ham dissection made on a cold, split carcass to show the joint to be separated.

[1] Weight information based on 12 measurements of carcasses from industrial trials at NMBU between 2019.09. – 2020.02.

Figure 1. Manual grasping and cutting of the front limb. The manual trajectory of the operators grasping hand is mainly downwards to support the limb when the cut is finalised along the neck.

Figure 2. Grasping of the hind leg is quite similar to the front leg but the trajectory to support the cutting is different. **Greater** downward force is needed to expose the joint between femur bone and the H-bone to the operator.

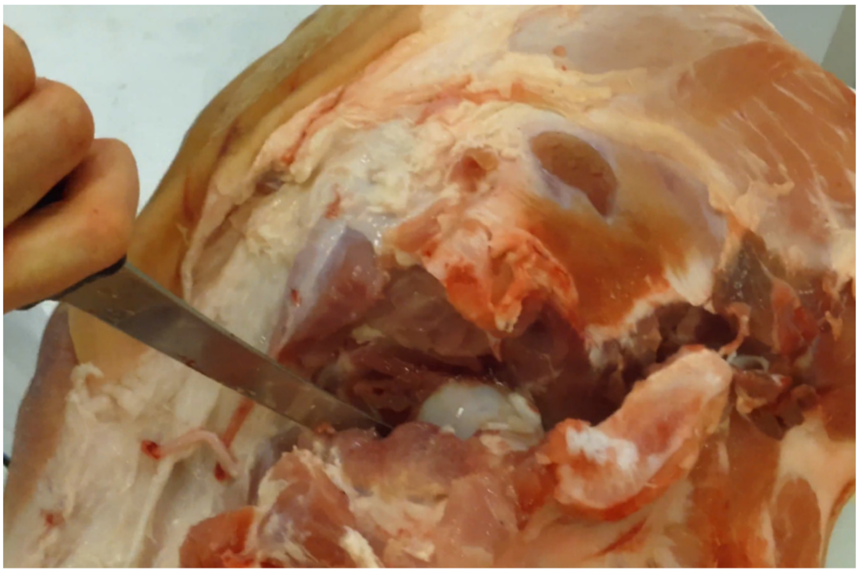
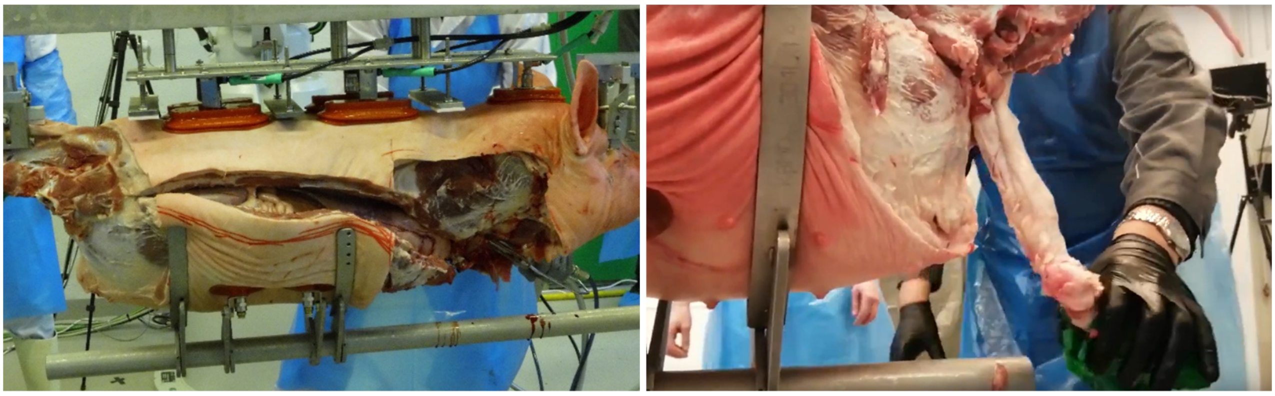


Figure 3. The joint between femur and the H-bone is visible as the ham is gradually pulled downwards. Please note that the image is from a split carcass.

The shared task for both procedures is to hang the four primals onto a metal frame for the veterinary inspection. One major challenge in this final trajectory is the large torque that occurs when the limbs are separated. During cutting of the limb, it is supported by the rest of the carcass so the weight load for the gripper is limited. This load gradually increases as the cutting is proceeding. When the last tissue is cut all the gravitational force of the limb, acting on the centre of gravity, needs to be counterbalanced by the gripper. The distance from the grasping point to the centre of gravity generate a risk of imposing a torque (force times distance) on the gripper/object interface. The torque needs to be under control not to damage the skin surface of the limbs as they are often used for skin-on, high value products. The control of the imposed torque on the skin surface may be done by a further support included in the gripper arm or by aligning the gripping point and centre of gravity with a vertical orientation.

1.3. Grasping inner organs

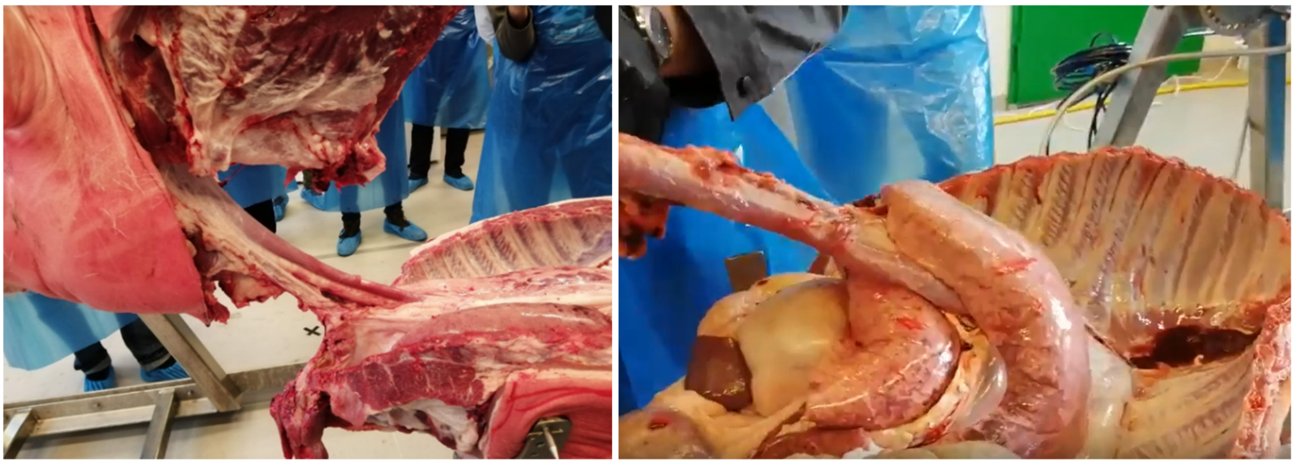
The grasping of some of the inner organs is necessary for the removal of the pluck and the intestines, since connective tissue must be torn or cut between belly or the saddle and the organs. The organ removal takes place after all the limbs are removed, the carcass is rotated 180° around its longitudinal axis (such that the back/spine are now in the top-most position), and the ribs are cut longitudinally on both sides (see Figure 4a). Additionally, it is required for the belly (the abdominal wall) to be pinned to the CHU and for a proper bone around the sacrum to be fixed to the CHU.



(a) *(b)*

Figure 4. (a) The state of the carcass at the beginning of the organ-removal process, and (b) the pulled-down rectum[2].

At this point, the saddle should be lifted a little and the first gripping-task occurs, when the sealed rectum has to be located, grasped and pulled down through the split pubic bone, to make the mediastinum approachable for the cutting tool from above the rectum (Figure 4b). Since the target object is soft, elastic and can be torn relatively easily (resulting in serious contamination), it is crucial to use a gripper that by design ensures that the grasped tissue remains intact. Furthermore, it is proposed that a marker should be placed onto the rectum after its manual sealing process, making it easier to locate the grasping point. BYTEMOTION proposed the use of ArUco markers[3], a widely used marker-system in augmented reality systems that are capable of 6 DoF tracking too (position and orientation, that might be required for locating cylinder-like elongated objects).



(a) *(b)*

Figure 5. (a) The graspable trachea and (b) the state of the belly part when the diaphragm should be cut.[4]

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[2] Photos taken at the 1st RoBUTCHER demo-cut at NMBU, 2020.02.18.

[3] ArUco Board documentation, "https://docs.opencv.org/3.4/db/da9/tutorial_aruco_board_detection.html", cited 29.04.2020

[4] Photos taken at the 1st RoBUTCHER demo-cut at NMBU, 2020.02.18.

The second gripping task, regarding the inner organs, occurs after the mediastinum (and some more connective tissues in the neck) is cut through up to the larynx. When the trachea – together with the oesophagus – is the only connection remaining between the saddle and the belly (see Figure 5a), the trachea should be grasped below the larynx, and cut through above it (preferably by an integrated cutting-tool in the gripper), completely separating the saddle from the belly. After the trachea is grasped and separated from the saddle, the pluck should be torn out of the belly by pulling the firmly grasped trachea in posterosuperior direction. When the diaphragm becomes visible and reachable for the cutting tool, the pulling should stop, and the muscle should be cut through (see Figure 5b). After the necessary cuts, the pulling should continue until all the organs are torn out of the belly.

2. Methods

2.1. Review of the State-of-the-Art

To provide a complete overview of the related landscape, we reviewed the recent results of soft material grippers, based on the PRISMA methodology[5]. Using such approach is very efficient in identifying papers in the included databases but it must be mentioned that some might be missed even if they are relevant, when they are not published in the selected databases.

We explored Google Scholar, NCBI Pubmed, IEEE Xplore and general search engines to collect possible results published in the last 5 years on the following key phrases (patents excluded):

- Meat gripper
- Soft tissue gripping
- Meat processing gripper
- Red meat processing robot
- Robotic pig slaughter
- Pig slaughter automation

It was revealed during the research that out of the 6 key phrases, only the first 3 provided useful results, the latter 3 failed to reveal new and relevant papers (also the NCBI database seemed to be irrelevant from our aspect). During the paper-identification process the goals of the whole RoBUTCHER project were always kept in mind for potential useful resources, in addition to the direct goal of this deliverable. Papers presenting innovative gripper-designs were our primary focus, however, papers about software and simulation related to robotic grasping were also included in the detailed review process. As a result, there are some records in the final collection that are not intended to help directly in the gripper-design, but found to be potentially useful in other work packages (e.g. the work of Misimi *et al*[6] might be interesting in WP3, as it presents a method about a robot "learning from demonstration").

The PRISMA flowchart of the scientific paper review process was as illustrated in Figure 6.

[5] http://www.prisma-statement.org/

[6] E. Misimi et al. "Robotic Handling of Compliant Food Objects by Robust Learning from Demonstration," IEEE/RSJ IROS, Madrid, 2018, pp. 6972-6979.

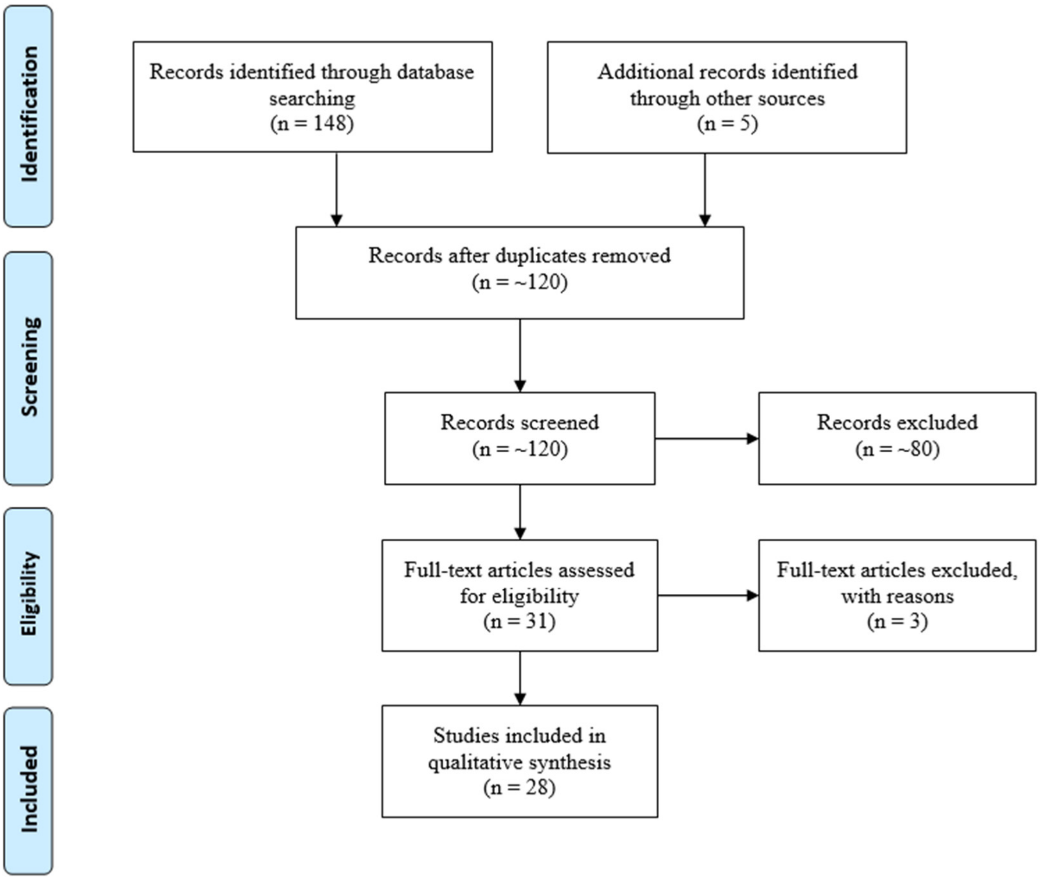

Figure 6. PRISMA flow-chart about the scientific-paper research.

Further, a patent database search was ordered from WIPO (World Intellectual Property Organisation), within the classes: b23 (machine tools for shaping) OR b25 (hand tools for shaping) OR g05 (controlling or regulating) OR b29c (shaping or joining of plastics) OR b65g (transport or storage devices) OR b66c (devices for cranes) OR f15b (systems acting by means of fluids in general) OR f16b (devices for fastening, eg. Clamps) OR g01 (measuring or testing) OR h01 (basic electric elements) OR h02 (generation, conversion or distribution of power) OR h04 (electric communication technique) with the following relevant search key terms:

- Gripping or
- Clamping or
- Damping or
- Finger or
- End-of-Arm

and:

- Robot or
- Robotic

The gross list consists of more than 200 applications dating back to 1983. The gross list covers a wide range of application areas with some deemed only to be relevant for industries other than the food industry. Excluding such specific industry applications, 98 remaining applications have been assessed for relevance for the RoBUTCHER project. The assessment is made from two points of view: commercial availability and relevance in addition to potential impediment of freedom to operate.

2.2. Principles

Focusing on the practical aspects of the encountered solutions in the publications, an overall table has been collated.

The ***gripper state of the art reference table*** is accessible for contributors in Teams, WP05 Files, T5-1. It is also included, as a snapshot at time of submission, in Appendix 1 of this document.

The working fields of each item identified include:

- Topic covered
- Title
- Authors
- Type of paper (on gripping theory or application)
- Topic
- Utility for the RoBUTCHER project (0-10)
- Brief summary
- URL for direct access (all reviewed papers are uploaded into Teams in PDF format)
- Technical specifications (e.g. weight, sensing type, etc.)

The relevance for the RoBUTCHER project and the technical parameters of the published designs and concepts observed during the research are reported in the next section.

2.3. Identification of key characteristics

This section of the document provides information regarding the specific gripping solutions identified as having importance with respect to the project. In Table 1 the general technical parameters of robotic grippers are listed along with the importance regarding the grasping tasks in the RoBUTCHER project. While all of the listed characteristics are important for gripper-development, number '2' in the importance column indicates that the given aspect is more important in the RoBUTCHER project than the rows with '1'.

3. Overview of the State-of-the-Art research

The state-of-the-art research about robotic grippers was carried out on two main domains: amongst the recently published scientific papers and amongst the available patents. The structure of this section is based on these two different paths.

3.1 Relevant scientific papers

3.1.1. Identification of papers

This section contains the detailed study of the 28 papers listed as "Studies included in qualitative synthesis" in the PRISMA flowchart in Section 2. The goal of the scientific paper research was to discover new perspectives and unique ideas about the whole meat (or soft tissue) gripping process. Finding a design that fulfils all the requirements that can be directly used in the RoBUTCHER project was an unlikely outcome. Thus, the collection of scientific papers chosen for thorough review includes gripper-designs based on unusual principles, soft-tissue related software, simulations and surveys.

The final set of papers was established with the following method:

1) Search for the key-phrases in the mentioned collections with the following restrictions:
    a. Published in 2016 or later;
    b. Patents excluded;
    c. Arranged based on relevance.

Table 1. Overview of analysis criteria for the meat industry grippers.

Characteristic	Description	Importance
Commercial	Yes or No. In detailed description, off the shelf availability, links, etc. should be collected.	2
TRL	1–9, according to EC.	2
Gripper type	The working principal of the gripper: mechanical, adhesive, freezing, etc.	2
Max gripping force	In Newtons. Minimum requirements are 200 static + scaling for the dynamic motions, depending on the exact task.	1
Max size of gripping	In cm, how big is the object to grasp.	1
Min size of gripping	Maximum possible closure of the gripper, in cm.	2
Mode of actuation	Electronic, pneumatic, hydraulic, etc.	2
Speed of actuation	Time to open/close. Typical time of operation, setup time, lag in operation.	2
Industry grade	Approved for the meat industry? Yes or no.	2
Cleaning/sterilizing method	What methods are applicable?	2
Mounting method	Conformability with standard flanges.	1
Weight of the gripper	Total weight, total payload allowed.	1
Size of the gripper	Dimensions.	1
Costs	Anticipated purchase cost, TCO, maintenance cost, etc.	2
Complexity	Overall complexity of the tool, a derivation of the physical properties, mostly enumerated above.	2
Sensory integration	Type of integrated sensors, options for extensions.	1

2) Save the relevant papers (only a few could not be accessed). Examples of discarded topics that came up frequently:
   a. Micro-grippers;
   b. Studies about "biological grippers" (e.g. different types of tongues);
   c. Grippers for packed food;
   d. Papers only mentioning, but not focusing on grippers.
3) Remove duplicates.

The process resulted in 28 papers: 17 presenting novel gripper-designs, 3 papers about software developed for reliable gripping of soft tissue, 3 presenting simulations about robotic gripping tasks, and 5 surveys or gripper-review articles. In the next sections these groups will be reviewed, excluding the survey-review group since its purpose was to grant a general knowledge about robotic gripper types and principles for soft tissue manipulation.

3.1.2. Gripper designs

The majority of the articles reviewed are presenting novel gripper designs. All of the available technical specifications are collected in an Excel table (see Appendix 1) thus here only a textual summary will be presented focusing on the classification of relevant ideas and approaches.

Despite the efforts to exclude the design-ideas during online-searches, i.e. those that cannot be implemented in our gripping-tasks, some gripping-principles that turned out to be unusable due to different reasons still showed up in the final collection. These gripping methods were the ones based on gripping with suction cups (not practical for the grasping of cylindrical objects), and some principles that can work well on a small-scale (e.g. in laparoscopic applications) but cannot be scaled up to our domain (e.g. grippers using Coanda-effect or capillary-effect).

The remaining 11 "design"-type papers can be designated as the main outcome of the state-of-the-art research among scientific papers, thus these are the items that the technical specifications are given for in the 1st appendix. All of these designs contain at least parts or concepts that could be used in the gripper-developing process in RoBUTCHER, considering the tasks, goals and specifications described in Section 1.

Potentially, the most complex type of robotic grippers is the advanced prosthetic hands and the hand-like grippers. The basic goal of these is to be as similar to a biological hand as possible, so the most advanced designs have 5 fingers, up to 24 DoFs, tactile-feedback and sometimes skin-mimicking coatings. Although these products are far too complex and complicated for our application, a strong enough design could probably achieve our goals too. The payload of this type of gripper is, however, usually 1-2 kg; the highest found was 12 kg, which is still not sufficient. A simplified "hand" with only 2-3 fingers, less DoF, but similar gripping-method could be a possible solution.

Figure 6. Examples for hand-like gripper designs.[7] [8]

Another type of gripper could be interpreted as a "simplified hand", namely the grippers with under actuated fingers. These grippers have significantly more (sometimes infinite) DoFs than actuators, thus the bending-trajectory of the fingers during grasping depends on the shape of the target-object. This behaviour makes under actuated grippers a popular choice for meat- and soft- tissue manipulation tasks, since it can eliminate the effect of biological variation by design (e.g. the diversity of the diameter of the tracheas or legs at different pigs). Most of these solutions are based on tendons actuating more than one joint. A software-design was found presenting a mathematical approach to the alternation of the behaviour of under-actuated grippers by modifying the friction of the joints. Another useful paper in this category described a tele-manipulated 3D

[7] Sean Casley et al. "*The IRIS platform - a prosthetic device including force sensing*", https://bit.ly/2MfgC5f, 2014.

[8] V. Kumar et al. "*Fast, strong and compliant pneumatic actuation for dexterous tendon-driven hands*". 2013 IEEE International Conference on Robotics and Automation. May 2013, pp. 1512–1519.

printed gripper with four sensor fingers and a sensor-enabled haptic-glove. The 3D printed gripper obviously is too weak for RoBUTCHER, but the haptic-glove and tele-manipulated gripper approach could be interesting in WP03 (e.g. for a knife-holding gripper).

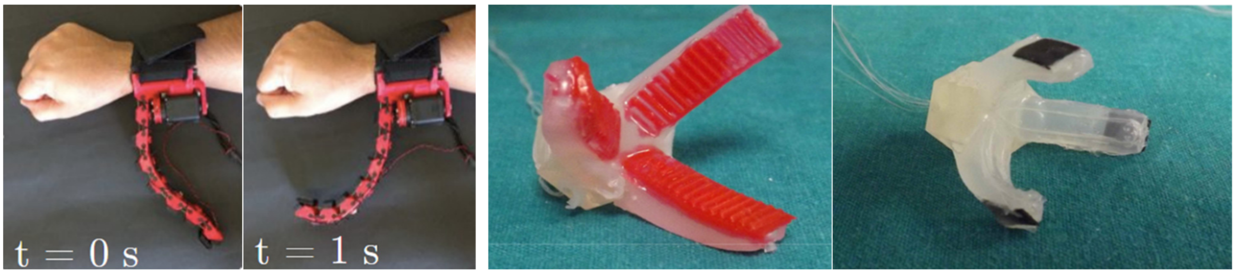

Figure 7. Examples for under actuated gripper-fingers[9,10].

One more frequently used approach for soft-tissue manipulation is a design that uses stick-like fingers moving radially. The advantage of these grippers is their simplicity: one motor can move all the fingers, force-control is relatively easy to implement and the cleaning of the fingers is simple (since there are usually no electronic or mechanical parts inside the fingers touching the objects). The fingers can be made of many appropriate materials and can have complex shapes; however, these designs are sub-optimal for the grasping of flexible cylindrical objects, they work best with highly deformable target-objects.

Figure 8. Example for a single DoF gripper with rod-like passive fingers[11].

3.1.3. Software and simulation

The smaller but still important part of the paper-collection are the papers presenting software for gripping applications and simulations about soft-tissue gripping. These papers usually operate with simple grippers, array of suction cups, few DoF fingers or casual 1 DoF grippers made up of only one open-close mechanism (examples are shown on Fig. 9).

The usual goal of the presented methods is to find an optimum using virtual mechanical models, artificial intelligence and/or simulation. The subject of the optimization can be either the gripper itself (e.g. finding the

[9] Salvietti Gionata et al. "*Design of the Passive Joints of Underactuated Modular Soft Hands for Fingertip Trajectory Tracking*" Robotics and Automation Letters. PP. 10.1109/LRA.2017.2718099, 2017.

[10] Giovanni Rateni et al. *"Design and Development of a Soft Robotic Gripper for Manipulation in Minimally Invasive Surgery: A Proof of Concept"*. Meccanica 50.11, pp. 2855–2863, 2015.

[11] G. Endo and N. Otomo. *"Development of a food handling gripper considering an appetizing presentation"*. IEEE International Conference on Robotics and Automation (ICRA), pp. 4901–4906, 2016.

optimal length of phalanges or the optimal friction of joints in an under-actuated mechanism) or the gripping movements and trajectories. In the RoBUTCHER project both approaches could be used for gripper-development, however, the latter might be more interesting. In our case, the shapes and positions of the target objects are known (roughly), but there is no available database or documented attempt for robotic trachea grasping, thus simulation and optimization of the grasping directions and trajectories might be effective.

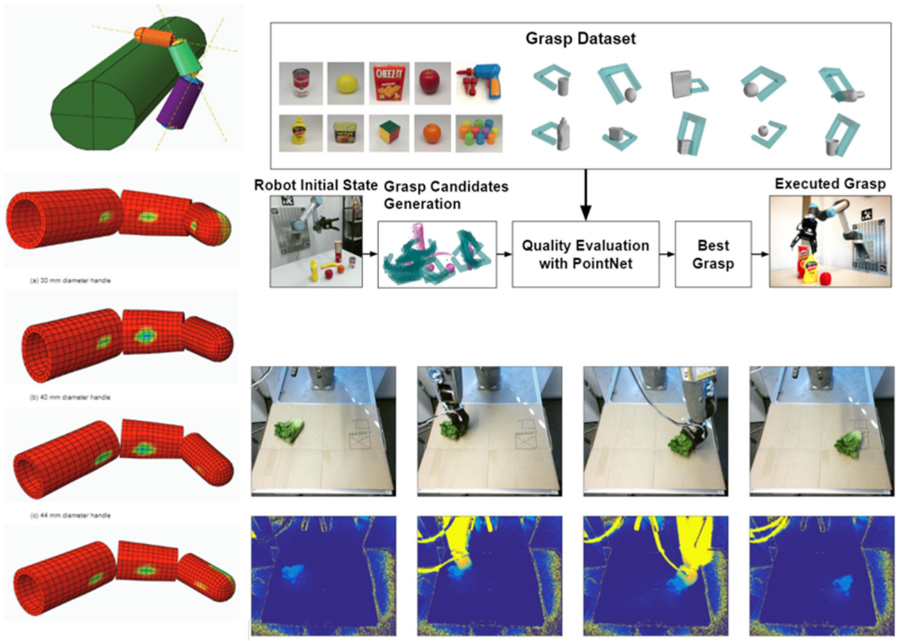

Figure 9. Examples of machine learning and simulation for gripping-optimisation[12,13,14].

3.2. Details of the grippers

3.2.1. DMRI custom tool

The dexterous gripping tools will be based on a prototype manual gripper designed by DMRI, developed for moving hams and fore ends. One major feature of the gripper is that it forms a bulge in the skin and subcutaneous fat as an effect of gripping. The snare function may fix the limb during support and transition to a display frame.

The prototype does not include sensors, but has a design that does not impose permanent marks on the skin of cold products. A similar feature on warm products must be confirmed in the present project, together with eventually inclusion of necessary sensor-based dexterity and intelligence, e.g. grasp quality detection and slippage prediction.

[12] Benedict Jain et al. "*Finite element analysis to assess the biomechanical behavior of a finger model gripping handles with different diameters*". Biomedical Human Kinetics 11.1 (2019), pp. 69–79.
[13] H. Liang et al. "*PointNetGPD: Detecting Grasp Configurations from PointSets*". International Conference on Robotics and Automation (ICRA). May 2019, pp. 3629–3635.
[14] Ekrem Misimi et al. "*Robotic Handling of Compliant Food Objects by Robust Learning from Demonstration*" IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Oct 2018, pp. 6972–6979.

Figure 10. The DMRI prototype of a simple non-dexterous gripper for hams Photo: courtesy of DTI-DMRI.

The sensor-based dexterity topic will be investigated with inspiration from a similar, very recently started DT-FOF-12-2019 RIA project, concurrent to RoBUTCHER. The APRIL project (870241) organized by the LifeSTech department at the Polytechnical University of Madrid is addressing robotic manipulation of small meat products among other flexible materials.

Furthermore, the physical moment imposed on the limb under some manipulation and orientations must be handled with a modification of the present hardware to reduce the risk of damaging the skin of the extremities. The DTI-DMRI gripper is found to be a good basis for the development of the trachea-grasper too. Since at this early point of the project the amount of remaining connective tissue around the trachea cannot be foreseen (see Figure 5a), the gripper must be able to grasp the trachea and the surrounding soft tissue in various circumstances by design (early approximation for possible target-diameters: from 3-4 cm up to 10-12 cm). This uncertainty will probably make the implementation of one more gripper-hand necessary (see Figure 11b) in such a way, that one bigger hand would first round up and compress the trachea and the adjacent tissues with a circular motion, then the second (smaller) hand would easily grasp and fix it. When the trachea is grasped firmly, it will be cut through either with an integrated scissor-like cutter or with the knife held in the other robot arm.

3.3 Patents with relevance for the RoBUTCHER activities

In section 2.1 the patent search was briefly introduced. It is restricted to international patents issued by WIPO. The search is important for two main reasons: The risk of using development resources for already existing solutions; and the risk of limiting our Freedom to Operate (FTO) within the project. The latter being of utmost importance for the commercial partners in the project, as the FTO refers to whether it is commercially “safe” to make or sell their products without infringing existing third-party IP rights.

The aforementioned complete list of more than 200 patents is reduced to 11 relevant patents and they are reviewed here. In Table 2 the text in italics is taken from the application abstract and our comment is in plain letters underneath.

Table 2: The list contains the patent applications that are assessed relevant for RoBUTCHER. The left column contains the application reference (incl. year of submission) and the title. The right column contains an extract of the published abstract (in italic) and our comments.

WO2009057416 GRIPPING APPARATUS AND GRIPPING APPARATUS CONTROL METHOD	*"A gripping apparatus comprises an information acquisition unit configured to acquire information about a position and orientation of an object to be gripped by a gripper, a movement path generating unit configured to acquire a target state suitable for gripping the object, based on the acquired information, and generate a movement path of the gripper toward the target state, and a controller configured to move the gripper along the generated movement path and cause the gripper to grip the object."* The present patent from 2009 is very generic, claiming a combination of a gripper, a movement path generating unit and a controller! Also, six described embodiments contribute to the generic perspective in the description. This patent must be analysed when the RoBUTCHER development requires specific solutions.
WO2011081851 ONE MOTOR FINGER MECHANISM	*"A mechanical finger comprises a plurality of phalanges coupled to a single actuator using a kinematic linkage and a differential linkage arranged in parallel. The mechanical finger is capable of exhibiting consistent predictable motion when moving in free space or when contacting an object at the fingertip, and of curling in order to conform to an object when the contact is at other locations on the finger."* Description of quite a dexterous under-actuated motor driven finger that could candidate as a possible solution in case higher degree of dexterity is required.
WO1999042800 FINGER TOUCH SENSORS AND VIRTUAL SWITCH PANELS	*"A device for detecting contact pressure applied to a finger, the finger having a fingernail illuminated by light, comprises at least one photodetector for measuring a change in light reflected by the fingernail in response to the contact pressure applied to the finger. The photodetector provides a signal corresponding to the change in light reflected. The device also includes a processor for receiving the signal and determining whether the change corresponds to a specified condition. The photodetector may be enclosed in a housing and coupled to the fingernail."* The patent describes a tactile finger sensing solution based on simple light reflection. The patent is issued to MIT (Massachusetts Institute of Technology) and related to the two-decade effort to bring a natural sense of touch to artificial hands and grippers, including the quite recent Gelsight sensing concept.
WO2017134076 ROBOTIC GRIPPING DEVICE SYSTEM AND METHOD	*"A robotic gripping device, system and method is described. The robotic device comprises an end effector having at least one finger, the fingers being capable of manipulating objects in the vicinity of the device under computer control. The device is capable of manipulating objects of varying sizes, dimensions and positions with reference to the device, without requiring information as to the precise location of the object with reference to the device."* Again, a very generic patent, here aiming for manipulating an object with a gripper without the knowledge of the precise position of the object! The potential of such solutions seems obvious but they may be contained in this patent application from 2017.
WO2012129288 ROBOTIC HAND WITH CONFORMAL FINGER	*"A robotic finger assembly can include a base for mounting the finger to a robotic hand, with the base having a motor, and at least three links. The links of the robotic hand are connected to each other and to the base by a series of joints. A joint shaft and a pivot shaft, where the pivot shaft can freely move within its respective joint shaft, is connected to a preceding link. The motor is activated for opening or closing the finger. The finger closes on an object with a distributed force across the links. Grasping also can mean engaging an object like a human hand, by closing the first finger link until it engages the object, then closing the second finger link until it engages the object, then closing the third link until it engages the object. A robotic hand assembly is also disclosed."*

	This adaptive gripper is quite narrowly protecting a delicate mechanical solution to an under actuated finger, but the application of drive mechanisms seems scalable to industrial grippers.
WO2009026925 GRIPPING DEVICE, FOR EXAMPLE FOR A ROBOT	*"A gripping device arranged for gripping an article, such as a food article, in particular a piece of meat, said gripping device comprising at least two gripping parts pivotally suspended with respect to each other. At least one of the gripping parts is pivotally suspended and comprises a gripping arm and a gripping clamp wherein the gripping arm is adapted for carrying the gripping clamp. The gripping device further comprises a flexible belt-shaped material, which extends at least between lower parts of the at least two gripping parts."* A potentially low-cost solution based on a flexible belt to interact softly with the object. The rights may be owned today by the Marel Group.
WO2019075463 END OF ARM TOOLS FOR SOFT ROBOTIC SYSTEMS	*"Robotic grippers have been employed to grasp and manipulate target objects. One task posing relatively unique problems is the handling of meat products, which can be difficult to grasp with a conventional gripper due to the surface texture and malleability of the meat, among other factors. This is particularly problematic when the meat product includes a bone, which has different properties from the relatively malleable meat surrounding it. Exemplary embodiments described herein provide robotic grippers having one or more fingers and a layered plate. The layered structure defines grooves sized and configured to lead in and capture the bone structure of the meat product. The grooves provide a backstop for the meat as well as preventing rotation or translation of the bone structure, thus allowing a firm grasp to be secured on the meat product."* This application from Soft Robotics addresses directly the gripping of bone-in meat products. In the description a T-bone steak is shown. The patent is one in an extensive range of soft grippers from Soft Robotics. The claims are focused on the T-bone object but due to the generic claim wording they must be investigated when RoBUTCHER develops limb grippers.
WO2012106234 MESOFLUIDIC CONTROLLED ROBOTIC OR PROSTHETIC FINGER	*"A mesofluidic powered robotic and/or prosthetic finger joint includes a first finger section having at least one mesofluidic actuator in fluid communication with a first actuator, a second mesofluidic actuator in fluid communication with a second actuator and a second prosthetic finger section pivotally connected to the first finger section by a joint pivot, wherein the first actuator pivotally cooperates with the second finger to provide a first mechanical advantage relative to the joint point and wherein the second actuator pivotally cooperates with the second finger section to provide a second mechanical advantage relative to the joint point."* The mesofluid actuation provides very high-power density from small mechanical devices and the patent protects such technology applied in a robotic gripper. As the flow volume is small the potential of high-speed actuation is available by mesofluidic hydraulics. The main claim 1 leaves not much room to operate without inflicting this patent.
WO2019118383 SENSORIZED ROBOTIC GRIPPING DEVICE	*"A robotic gripping device is provided. The robotic gripping device includes a palm and a plurality of digits coupled to the palm. The robotic gripping device also includes a time-of-flight sensor arranged on the palm such that the time-of-flight sensor is configured to generate time-of-flight distance data in a direction between the plurality of digits. The robotic gripping device additionally includes an infrared camera, including an infrared illumination source, where the infrared camera is arranged on the palm such that the infrared camera is configured to generate grayscale image data in the direction between the plurality of digits."* The patent describes the application of a 3D camera (ToF+IR vision) to survey the volume between the gripper digits with a field of view to recognize unknown objects, their orientations and positions. Our use of movable cameras fixed to the robot must make a distinct difference.

WO2012089928 METHOD, COMPUTER PROGRAM AND APPARATUS FOR DETERMINING A GRIPPING LOCATION	*"According to one aspect of the invention, there is provided a method com- prizing: obtaining at least one image comprising at least one object; analysing the at least one image to determine at least one gripping location to grip an object; selecting a gripping location from the at least one gripping lo- cation based on a predetermined criterion; and issuing at least one instruction to a gripper to grip the object at the selected gripping location."* The patent is aiming at bin picking of industrial products in random positions. However, claim 1 is very generic describing the use of a pre-recorded image of the object of interest to estimate an optimum position of the grasping.
WO2012156579 METHOD AND APPARATUS FOR MOVING AND POSITIONING A GRIPPING UNIT, AND A ROBOT PROVIDED WITH GRIPPING UNIT	*"A method and apparatus for moving and positioning a gripping unit, in which method the gripping unit is moved and positioned by intermediation of cables so that at least one degree of freedom of the gripping unit is removed by fastening the gripping unit mechanically support structure. The invention also relates to a robot provided with this kind of apparatus."* The patent relates to a delta type of robot for handling waste on a conveyor controlled by a vision system. Even though the application seems distant from RoBUTCHER, the application of a vision control system must be observed in our application of a range of vision systems.

3.4 Current EU projects within DT-FOF-12-2019

To investigate the potential inspiration and synergy with current project within the DT-FOF-12-2019 topic a search in CORDIS for relevant projects results in a list of four started projects:

3.4.1. Manipulation Enhancement through Robotic Guidance and Intelligent Novel Grippers

MERGING will deliver a turnkey robotic solution to automate handling of flexible and fragile objects.

Our ambition is to provide manufacturers with an end-to-end solution to automate the handling of soft objects. The solution will consist of a multi-finger gripper equipped with an electro-adhesive skin that conforms to the objects to handle even delicate fabrics or components without any damage. Electro-adhesion increases the direct gripping forces and thus allows greatly reduced clamping forces. Our solution includes perception and supervision functions to adapt the system's behaviour in real time to the execution conditions and for robot system programming accessible to non-specialists.

Our main motivations are to build a versatile, easy-to-use and low-cost system. To demonstrate this and the possibilities of scaling up, we will design our system using proven laboratory technologies (TRL 4), then carry out proof of concept in realistic environments (TRL 6) in three different applications and sectors: fabric handling for lingerie manufacturing, technical fibre handling for composite bus panel manufacturing, and plastic bag handling for the food industry.

MERGING is a three and a half year project involving the entire value chain of soft object gripping automation. The CEA leads the project and provides the robotic technologies in collaboration with EPFL (electrical adhesion), AIMEN (perception), LMS (supervision), and SHADOW (capture) and IPC (materials). CEA, EPFL, AIMEN and LMS will respectively use AI technologies for robotic demonstration programming, electro-adhesive skin control, perception and control of the complete system. SELMARK, VDL and THIMONNIER introduce cases of use of fabric, composite and polymer handling respectively. CASP and ACTEMIUM are respectively responsible for the software and hardware integration and the exploitation of the results. SHADOW will release the pliers with electro-adhesive skin after the end of the project.

3.4.2. Multipurpose robotics for mAniPulation of defoRmable materIaLs in manufacturing processes

APRIL project aims at implementing and deploying market oriented, low cost and multipurpose robots that supports semi-automatic tasks in manufacturing production lines that use flexible or deformable materials in industries of any size or domain.

APRIL will use fine grasping, innovative computational vision technology, gathering of sensors' information, as well the development of modular and different middleware layers and interfaces. APRIL will provide innovative sensors and computational vision supporting detection of slips, estimate weight, dynamic centre of mass, or regulating grasping forces while manipulating deformable objects of different types (e.g. paper, chicken breast, shoes' insoles, viscoelastic textile materials, cables, etc.). A federated approach, wireless communication, usage of multipurpose hands and placement of various sensors, will connect all robots to a cloud based knowledge base that will contain the needed information to perform the different jobs.

APRIL system will be deployed in six different demonstration use cases across Europe. Robots integrated in the manufacturing processes will operate on several critical steps that affect production, packing and quality assurance on the different manufacturers involved as pilot sites. On one hand, introduction of APRIL system will produce an expected increase on safety and related health conditions of working environments. On the other hand, APRIL will enable an increase on productivity and quality of the final products; thus leading to a greater competitiveness of European industry.

The project will be implemented in 40 months by 15 partners from 8 European countries.

3.4.3. Robotic tEchnologies for the Manipulation of cOmplex DeformablE Linear objects

The factory of the future will be fully automated. Right now, robotics have yet to replace all types of manual labour, particularly complicated tasks that involve the handling of complex materials and objects. Deploying robots for these tasks is necessary to ensure Europe can compete with countries having large labour forces. The EU-funded REMODEL project supports new production environments for manufacturing products with extensive wires and cables. It integrates a dual-arm robot in the production line for routing and fitting with advanced techniques. It will use the former WIRES project's tools to solve electric wire manipulation issues, as well as add new perception and interaction functions. This will be tested for effectiveness in four industrial cases.

3.4.4. Advanced RoBOTic Technology for Handling SOFT Materials in MANufacturing Sectors

Many tasks involving the handling of deformable objects – from surgery to packaging and food handling to automobile manufacturing – are done by skilful human operators. Advances in technology could one day have robots doing such work. The EU-funded SOFTMANBOT project will provide an innovative and holistic robotic system for the handling of flexible and deformable materials within labour-intensive production processes. Its system will include smart dexterous grippers that will enable grasping and manipulation skills with integrated sensors (mainly tactile). The project will test the technology in industrially relevant environments in four key manufacturing sectors (toy, textile, footwear and tyre). The findings will contribute to technological advances to help robots play a bigger role in European factories.

The projects deal with flexible material handling, but only the APRIL project includes case demonstrations within food, especially chicken meat handling. Despite the significant lower weight of the chicken products, the APRIL project is contacted for future inspiration and synergy.

4. Basis for decision

4.1. Stage 1

In the RoBUTCHER project, priorities have been given to the feasibility of the task execution, therefore at first, grasping solutions already available to perform a demo have been considered.

A gripping tool for this soft-tissue manipulation task should be able to grab the trachea knowing only the approximate gripping point and holding on to it firmly until the whole pluck is removed. Therefore, the gripper should be strong enough to allow the robot to tear the connective tissue between the pluck and the belly, hold and stretch the pluck while the diaphragm is being cut under it, and after it to tear the connective tissue between the belly and the intestines, removing the pluck and intestines (and the kidneys) all together. The whole object is approximately 15 kg, but the additional tearing-force should also be considered during calculations. It has already been demonstrated that the trachea itself might be strong enough to hold the weight of the pluck and intestines, and to withstand the force that is necessary to tear the pluck out[15]. However, it has not yet been tested if the trachea (and other guts) could withstand the force applied during the tearing of the intestines, cuts on the connective tissue might be necessary there.

The gripping tool for the limbs must provide enough force to fight gravity on the limbs after they are cut off the carcass. Due to the significant distance between the centre of gravity of the separated limb and the grasping point (resulting in a sudden high torque), there will be an additional challenge in coping with the stretching-effect of the moment not to damage the skin surface. The weight of the limbs is similar to the soft-tissue gripping but the moment is somewhat higher due to the rigidity and the offset centre of gravity. The dexterity of the present DMRI gripper is very low (2 DoF).

4.2. Stage 2

One striking feature with most examples from the scientific papers is the low payload of the grippers. Only two[16,17] have demonstrated a sufficiently high handling capacity for our requirements. Furthermore, the examples do have a weight/payload ratio below five and a design that will not optimally fit into our applications. Especially for the organ grasping, this ratio will contribute to the limiting kinematic factor at the start of the grasping process.

To conclude the key findings of the identified research is that

- The weight/load ratio too low for the described grippers
- Electric motors are used more often than pneumatic actuation for such high payloads
- Finger-based gripping is the only possible choice for the RoBUTCHER gripping tasks (e.g. vacuum-based gripping or special principles like Coanda-effect are not an option)
- No current off-the-shelf solution can accomplish these tasks

Given the complex user requirements of the project, it may be inevitable to develop a smart tool that performs the grasping and other requested tasks, such as cutting, categorisation, racking, etc.

In the RoBUTCHER project, it would be optimal to use the same tool for gripping the limbs and the trachea too, however it is not imperative. Such a tool will be developed with the cooperation of DTI-DMRI and OBUDAUNI, or a separate trachea-gripping tool will be developed.

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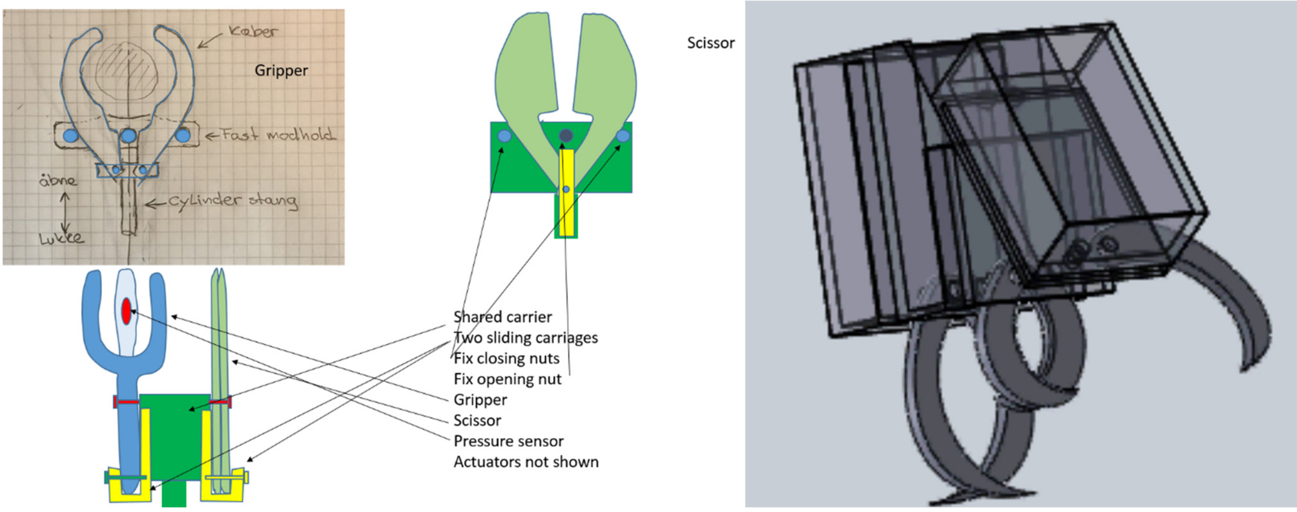
15 Information based on experiments at a RoBUTCHER meeting at NMBU, 2020.02.

16 J. Spiliotopoulos et al, “A Reconfigurable Gripper for Dexterous Manipulation in Flexible Assembly”, Inventions, vol. 3, iss. 1, 2018.

17 V. Kumar et al, “Fast, strong and compliant pneumatic actuation for dexterous tendon-driven hand”, IEEE International Conference on Robotics and Automation, 2013.

An initial sketch of the trachea gripper principle is shown in Figure 11 below.



(a) *(b)*

Figure 11. (a) A primitive sketch of the trachea gripper/cutter principle based on the mechanic driving mechanism of the DMRI gripper for the limbs, and (b) a primitive model for robust trachea grasping and cutting.

The patent survey must be taken into account e.g. when developing further improvements on the DTI-DMRI gripper to reduce the risk of infringing any protected prior art.

The tactile sensing feature of the trachea gripper will seek inspiration from the APRIL project.

5. Conclusion

As many of the scientific papers aim at developing prosthetic grippers/hands, very few will have the potential of surviving in an industrial food production. However, the ideas behind drive mechanics, power source and weight/payload ratio may give inspiration to the necessary activities of RoBUTCHER gripper design. The same may be said about the specific gripper patents and the generic patents that should be analysed in much detail when the design ideas are developed.

In conclusion, we recommend using the DMRI gripper as a start point for the RoBUTCHER activities. This gripper needs to be redesigned to reduce the gripper weight to improve the required kinematic capacity of the finger/hand/arm system. The ultimate goal is to modify the gripper up to the point when it will be able to carry out the limb- and the organ-gripping tasks too.

Due to the very high level of flexibility, the weight of the organ set will be shared between the gripper and the abdominal cavity so the contribution to the kinematic forces from a very heavy gripper will affect the grasping procedure negatively. A similar comment may be made for a direct application of the DMRI gripper to grasping the trachea. Therefore, the trachea gripper will be inspired by the gripping mechanism only from the DMRI unit and redesigned to include a second clipping function.

Finally, the included papers and patents should not be considered as an exhaustive list as the selection of search keywords, patent classes and paper databases may have excluded relevant publications and patents.

Appendix 1: Reference List

Reference archive, correct at time of submission. Internally, this archive is maintained as part of WP5, as a Microsoft Excel spreadsheet, and located in the project internal Microsoft Teams platform under the WP5 file structure.

#	Topic	Title	Authors	Type of paper	Utility	TRL	Payload	Driving power	DoF	Cost	Sensing type
7	Hand-like gripper	A Reconfigurable Gripper for Dexterous Manipulation in Flexible Assembly	Spiliotopoulos, Jason; Michalos, George; Makris, Sotiris	Design	8	7	15kg	Motor, gear wheels and shafts	8	NA	None
3	Review	State of the Art Robotic Grippers and Applications	Tai, Kevin; El-Sayed, Abdul-Rahman; Shahriari, Mohammadali; Biglarbegian, Mohammad; Mahmud, Shohel	Review	8	-					
8	Hand-like gripper	Fast, strong and compliant pneumatic actuation for dexterous tendon-driven hands	V. Kumar; Z. Xu; E. Todorov	Design	7	6	12kg	Tendons, Pneumatic and electronic driven	24	High	Pressure and position
22	Hand-like gripper	Design of the Passive Joints of Underactuated Modular Soft Hands for Fingertip Trajectory Tracking	G. Salvietti; I. Hussain; M. Malvezzi; D. Prattichizzo	Design	7	5	low	Tendons, electric motor	Under-actuated	NA	None
27	Hand-like gripper	Variable-Friction Finger Surfaces to Enable Within-Hand Manipulation via Gripping and Sliding	A. J. Spiers; B. Calli; A. M. Dollar	Design	7	5-6	low	Servos + tendon	2	NA	position, torque

#	Topic	Title	Authors	Type of paper	Utility	TRL	Payload	Driving power	DoF	Cost	Sensing type
28	Rods-based gripper	Rod-based Fabrication of Customizable Soft Robotic Pneumatic Gripper Devices for Delicate Tissue Manipulation	Low, Jin-Huat; Yeow, Chen-Hua	Design	7	6-7	<2N (surgical use)	pneumatic	1-2	low	NA
14	Machine learning	Robotic Handling of Compliant Food Objects by Robust Learning from Demonstration	Misimi, Ekrem; Olofsson, Alexander; Eilertsen, Aleksander; Oye, Elling; Mathiassen, John	Software	7	-					
5	Review	Soft Manipulators and Grippers: A Review	Hughes, Josie; Culha, Utku; Giardina, Fabio; Guenther, Fabian; Rosendo,;re; Iida, Fumiya	Review	6	-					
15	Survey	Requirements for a cloud-based control system interacting with soft bodies	D. A. Tomzik; X. W. Xu	Survey	6	-					
6	Prosthetic	The IRIS platform - a prosthetic device including force sensing	Casley, Sean; Choopojcharoen, Thanacha; Jardim, Adam; Ozgoren, Deniz	Design	5	6	500g	Tendons, mechanism	6 (?)	medium	Camera and drive motor current
11	Rods-based gripper	Development of a Food Handling Gripper Considering an Appetizing Presentation	G. Endo; N. Otomo	Design	5	5	NA	electric motors	2	low	none

#	Topic	Title	Authors	Type of paper	Utility	TRL	Payload	Driving power	DoF	Cost	Sensing type
25	Simulation	Finite element analysis to assess the biomechanical behaviour of a finger model gripping handles with different diameters	Tony, Benedict Jain AR; Alphin, Masilamany S	Simulation	5	-					
16	Machine learning	PointNetGPD: Detecting Grasp Configurations from Point Sets	H. Liang; X. Ma; S. Li; M. Görner; S. Tang; B. Fang; F. Sun; J. Zhang	Software	5	-					
26	Force sensing / Hand-like gripper	Finger-attachment device for the feedback of gripping and pulling force in a manipulating system for brain tumor resection	Chinbe, Hiroyuki; Yoneyama, Takeshi; Watanabe, Tetsuyou; Miyashita, Katsuyoshi; Nakada, Mitsutoshi	Design	4	Not a gripper-design					
1	Surgical	Design and development of a soft robotic gripper for manipulation in minimally invasive surgery: a proof of concept	Rateni, Giovanni; Cianchetti, Matteo; Ciuti, Gastone; Menciassi, Arianna; Laschi, Cecilia	Design	4	7	Low (MIS use)	electric motors	infinite (3 actuators)	low	cable-force
2	Force sensing	Hybrid Tele-Manipulation System Using a Sensorized 3-D-Printed Soft Robotic Gripper and a Soft Fabric-Based Haptic Glove	J. H. Low; W. W. Lee; P. M. Khin; N. V. Thakor; S. L. Kukreja; H. L. Ren; C. H. Yeow	Design	4	6	max 1 kg	pneumatic	infinite (4 actuators)	probably high	force

#	Topic	Title	Authors	Type of paper	Utility	TRL	Payload	Driving power	DoF	Cost	Sensing type
4	Prosthetic	An Adaptive Actuation Mechanism for Anthropomorphic Robot Hands	Kontoudis, George; Liarokapis, Minas; Zisimatos, Agisilaos; Mavrogiannis, Christoforos; Kyriakopoulos, Kostas	Design	4	5	500g	Tendons	14	Low	None
10	Coanda-effect gripper	Design And Optimization Of Single Head Planar Coanda Gripper	E. Natarajan; L. W. Hong; M. Ramasamy; C. C. Hou; R. Sengottuvelu	Design	4	Not relevant - Coanda effect cannot be used effectively with high loads					
23	Optimization	Robust optimization with applications to design of context specific robot solutions	Jorgensen, Troels Bo; Jensen, Sebastian Hoppe Nesgaard; Aanaes, Henrik; Hansen, Niels Worsoe; Kr"uger, Norbert	Simulation	4	-					
18	Machine learning	Toward Sim-to-Real Directional Semantic Grasping	Shariq Iqbal; Jonathan Tremblay; Thang To; Jia Cheng; Erik Leitch;;y Campbell; Kirby Leung; Duncan McKay; Stan Birchfield	Software	4	-					

#	Topic	Title	Authors	Type of paper	Utility	TRL	Payload	Driving power	DoF	Cost	Sensing type
21	Software	Model-free and learning-free grasping by Local Contact Moment matching	M. Adjigble; N. Marturi; V. Ortenzi; V. Rajasekaran; P. Corke; R. Stolkin	Software	4	-					
19	Survey	A Billion Ways to Grasp: An Evaluation of Grasp Sampling Schemes on a Dense, Physics-based Grasp Data Set	Clemens Eppner; Arsalan Mousavian; Dieter Fox	Survey	4	-					
12	Suction-gripper	An Adaptive Robotic System for Doing Pick and Place Operations with Deformable Objects	Jorgensen, Troels Bo; Jensen, Sebastian Hoppe Nesgaard; Aanaes, Henrik; Hansen, Niels Worsoe; Kr"uger, Norbert	Design	3	Not relevant - Using suction-cups					
20	Suction gripping	Design of a 2-DOF Delta Robot for Packaging and Quality Control of Processed Meat Products	Hilario Poma, Javier Alfredo; Galvan, Jose; Quispe, Ismael; Manzanares Grados, Ruth; Cordova, Francisco	design	3	Not relevant - Using suction-cups					
24	design	Capillary-based gripping for laparoscopic bowel surgery	van den Berg, Jay	design	3	Not relevant - Capillary effect can not be used effectively with high loads					

#	Topic	Title	Authors	Type of paper	Utility	TRL	Payload	Driving power	DoF	Cost	Sensing type
13	Simulation	Robust optimization of robotic pick and place operations for deformable objects through simulation	T. Bo Jørgensen; K. Debrabant; N. Krüger	Simulation	3	-					
17	Survey	Robotic manipulation and sensing of deformable objects in domestic and industrial applications: a survey	Jose Sanchez; Juan-Antonio Corrales; Belhassen-Chedli Bouzgarrou; Youcef Mezouar	Survey	3	-					
9	Suction-gripper	A flexible suction based grasp tool and associated grasp strategies for handling meat	Jorgensen, Troels Bo; Hansen, Bo Renneberg; Pedersen, Mads Moller; Kr"uger, Norbert; Hansen, Niels Worsoe	Design	2	Not relevant - Using suction-cups					

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