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Quality assessment of fresh meat cuts as a performance indicator of knives specifically adapted for robot-assisted operations

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A B S T R A C T

Manual labour in slaughterhouses is hazardous work. Workers suffer from injuries and occupational illnesses resulting from repetitive movements with sharp knives. There is a need for a robotic tool which can perform versatile tasks with a high level of precision. This knife must be able to imitate the same primary cuttings of a professional butcher and produce meat products which are acceptable to the end-market. This paper reports the results of a world-wide assessment of the fresh pork meat cuts as a performance indicator of knives specifically adapted for automated operation. These knives included Victorinox knife, bespoke double bladed Uddeholm knife, vibrating knife and novel smart knife with built-in sensing mechanism that detects in real time the contact with meat and cut depth. Physical appearances of cuts were assessed anonymously by independent responders with different backgrounds. All knives were deemed acceptable in terms of cutting quality. There was also no discernible difference of opinion between manual and robot cuts. This indicates that the new knife for robot-assisted cutting is acceptable by market.

1. Introduction

Slaughterhouse workers are especially prone to physical injuries, psychological distress and exposure to trauma (Victor & Barnard, 2016). The main tools for many operators are sharp knives. The combination of handling sharp cutting tools and an increasingly demanding production volume further exacerbates the potential for workers' injuries. 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 (*OECD-FAO Agricultural Outlook 2021-2030*, 2021). The U. S. The Department of Agriculture has enforced a limit on the number of pigs to be processed at a plant to 1 106 per hour to protect the employees' safety (United States District Court & District of Minnesota, 2021).

The challenge of work-related incidents is exacerbated by occupational illnesses typical for manual work in a slaughterhouse. 50 % of musculoskeletal disorders in work related to meat processing affect the fingers, hands, and wrists of the operators. In France, 30 % of musculoskeletal disorders occur in relation to work in the meat sector. This has a massive economic cost for society, but absenteeism also causes disruption to production which again generates further costs (Maithani et al., 2021). Reports from the USA state that injuries sustained within the pork meatpacking workforce have rates of over 2.4 times the

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national average. For employees requiring restricted duties or time off work, the injury rate increases to almost three times the national average (Ross et al., 2022). 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).

2020 brought the emergence of a new global threat from the COVID-19 coronavirus pandemic. 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 (Powell, 2020), 200 in Germany (Foote, 2020) and ten outbreaks resulting in 566 staff testing positive in Irish meat plants (Cullen, 2020). Norway has experienced closures at two red meat plants due to COVID-19 infection and resultant travel restrictions, which meant that migrant labour was scarce in comparison to previous years (Ross et al., 2022).

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). In recent years, slaughter lines have become increasingly characterized by automation. Robotic implementation increases efficiency and throughput and produces better quality. The robotic technology itself has also become better, more affordable and available (Alvseike & Mason, 2018). Compared to manual cutting, even basic cutting machines increase throughput and safety.

Generally, the automated solutions developed for slaughterhouses are adapted to large, high-volume processing, and usually only produce simple, effective, and uncomplicated primary cuttings. These solutions also adhere to the traditional slaughter line where the operations take place in succession and are dependent on the effectiveness and rhythm of the production line (de Medeiros Esper et al., 2021). A tool has not yet been developed which can perform dexterous, fine cuts and be able to perform versatile tasks on meat materials. Meat processing involves the handling of soft materials with inconsistent structure. Biological raw materials provide a bigger challenge to machines and robots. This is one cause of the gradual implementation of robotics in the meat industry. Development of robotic sensors which can determine the characteristics of a material, can improve automation in the industry (Alvseike & Mason, 2018).

The authors of this paper have researched the possibility of creating a robotic solution to the different large-scale automated systems already available in the meat industry. The RoBUTCHER project (RoBUTCHER 2020; https://robutcher.eu/ Accessed 2nd February 2022) seeks to create a new, state-of-the-art automated meat factory cell (MFC) where robots debone a pig carcass from the outside. All operations take place within a closed cell where a functional, robotised knife performs the cutting. Cut surfaces that are considered of acceptable quality for the market are necessary for the MFC processing (Alvseike et al., 2018). An acceptable cut surface appears even with no visible cuts and no remains of meat or other tissue attached to the cut surface (Håseth et al., 2020).

The basis of this research is the need for a safer, more effective knife with a high level of precision for use in automated meat processing. Meat processing is an industry that requires novel automated solutions to improve its sustainability and to mitigate harsh working conditions, shortage of skilled labour and not least, minimise impact of the recent pandemic. Automation of all or many processes is seen as the way forward, with robots performing various tasks instead of people (Alvseike et al., 2020; de Medeiros Esper et al., 2021). Meat cutting is one of these tasks.

Customer loyalty is a requirement for a product's success and product quality is therefore a central element (Garrido-Morgado et al., 2016). For a new product to survive in a competitive market, it relies on the loyalty of the customer which is a direct consequence of satisfaction with the product (Akhtari et al., 2015). Even though cuts made by the robot may be further processed, the robotic knife must be able to produce cuts of end-user satisfaction. It is therefore important to examine the market's perceived difference between manual and robotic cutting.

The aim of this study was to assess the quality of fresh pork meat cuts performed by different knives specifically designed and adapted for robotic cutting, compared with cuts performed by a skilled human butcher using a typical knife.

2. Materials and methods

2.1 Knives

There are many suitable cutting tools available for the professional butcher. These tools are usually "passive" knives which depend on the skills and experience of the operator. Knives adapted to robotic use in the meat industry must exhibit characteristics which can help the robot simulate human movements (Håseth et al., 2020).

Three different knives attached to a UR10 robot (Universal robots, Odense, Denmark) were tested to assess the quality of performed cuts as compared to those made by a human: a bespoke knife, a vibrating knife, and a smart knife. The cut surfaces were then compared to surfaces cut by a certified operator using a manual knife.

The knives tested were chosen because they exhibit characteristics which define a robotic knife suitable for use in meat processing. These characteristics must include the ability to mimic human movements, to be able to produce the same primary cuttings as a professional butcher. The readiness of the tool and adaptability to be attached to a robotic arm is essential. In a commercial application, the knife will have to be changed e.g., for resharpening, and the reattachment must thus be easy to perform. The weight of the knife should preferably be kept low. This allows for more precise movement because less force is needed to operate the tool. The capacity of the tool implies the cutting speed and the time required for grinding, cleaning etc. In industrial conditions, these operations must be quick and simple as not to interrupt the processes (Håseth et al., 2020).

The important factors are material stiffness and hardness, dimensions of the knife blade and sharpness of the edge, wear resistance, food grade and possibility of high electric conductivity. The knife should also exhibit some degree of intelligence to allow the robot to determine the material which is being cut and to deliver feedback to the robot (Håseth et al., 2020). The criteria for sensing approaches for smart knife implementation were set in (Mason, Romanov, Cordova-Lopez, Ross, et al., 2021). Based on these, electromagnetic spectroscopy was identified as one of the methods that could form a basis for a smart knife, as detailed in section 2.1.4.

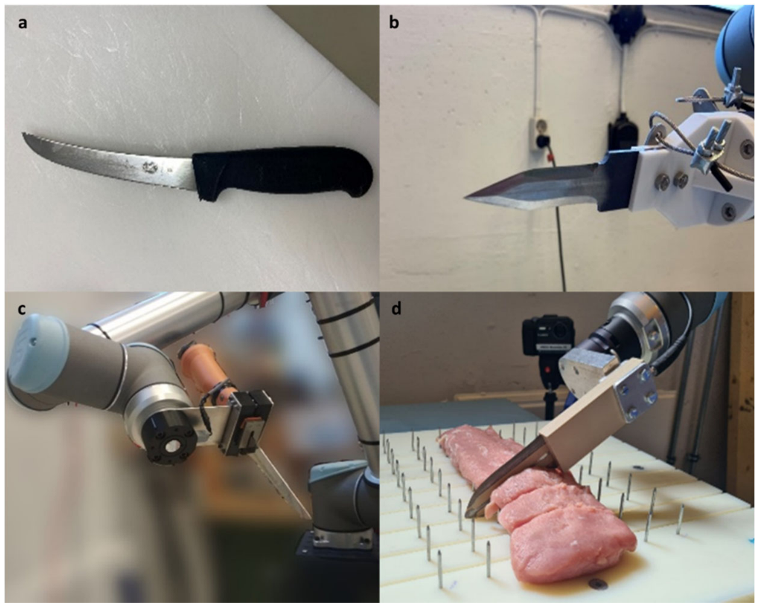

Fig. 1. The four types of knives used in the experiment: (a) The handheld Victorinox knife, (b) The bespoke Uddeholm knife, (c) The EFA 805 air operated power knife, (d) The Smart knife

2.1.1 Victorinox knife

The Victorinox curved boning 5.6503.15 knife (Victorinox, 2021) (see Fig. 1a) was chosen as a reference knife because it is easily commercially available and a popular knife with professional butchers. It is a deboning knife which means it is intended to cut meat off bones. It is made of stainless steel with a Rockwell hardness scale (HRC) of 56 The blade length is 150 mm with a 25 mm blade height, and 1.6 mm blade thickness. The material of the handle is a thermoplastic elastomer and the weight is 100 g (Håseth et al., 2020).

2.1.2 Uddeholm knife

The steel producer Uddeholm AB delivers bespoke knives upon request. The knife delivered to this project was customised with two edges and made of Vanadis 4 Xtra steel. The finished design is shown in Fig. 1b This steel is of 60 HRC and is suitable for the production of knives. The blade length is 73 mm, the width is 18.5 mm, and the thickness is 2.9 mm. The weight of the knife is 78 g. The edge of the knife was designed to be short compared to handheld knives such as the Victorinox with an even blade thickness and straight cutting edges. The length of the blade was preferred to be short because it would make it easier to produce and regrind the knife (Håseth et al., 2020).

2.1.3 Vibrating knife

The EFA 805 (EFA Elektro AS, Oppegård, Norway) air operated power knife (see Fig. 1c) is intended for use in meat trimming and processing. It requires a motor output of 300 W and has an air consumption of 20 cubic feet per minute (cfm). The operating pressure is 6 bar. It functions by moving backwards and forwards at a speed of 20 000 times a second. The weight of this knife is 790 g (EFA, 2019). Different knife blades can be attached to the shaft and during these trials a meat knife with 14 cm length was used.

2.1.4 Smart knife

Microwave technology is very safe, posing no threat to operators (Allen, 2021). This technology takes advantage of the differing dielectric properties ($\varepsilon^* = \varepsilon' - j\sigma$, ε' = permittivity and σ = conductivity) of biological tissues, where an antenna transmits pulses into the tissues, resulting in a frequency-dependent diversion and scattering at the interface between differing tissues (Marimuthu et al., 2021; Mason et al., 2018). There are several values that can be used to describe the dielectric properties of a material, but the most common is its permittivity. The design flexibility offered by microwave sensing to suit a range of applications is another reason why this sensing approach may be considered by the meat industry for assistance in automated cutting to construct an intelligent cutting tool.

The smart knife, shown in Fig. 1d, was developed especially with meat processing in mind. This knife is based on the physical design of the bespoke knife created by Uddeholm AB and has an integrated sensing element which provides feedback to the robot about the cutting process (contact or no contact and the depth of the cut), and potentially about the material which is being cut.

The overall length of the knife is ca. 250 mm, while the blade is ca. 125 mm (body to tip). The body is 45 mm wide. The overall shape of the blade gives two broad cutting edges, reducing the need for reorientation of the knife when performing several passes to complete a cut (Mason, Romanov, Cordova-Lopez, & Korostynska, 2021).

The performance of the smart knife in terms of its ability to predict the contact and depth of cut was reported in (Mason, Romanov, Cordova-Lopez, & Korostynska, 2021). Partial-least-square regression and neural network prediction models are shown to determine contact of the knife with a work object and depth of cut. Using a water model, the knife can predict contact with 1.81% error, and depth with 2.45 mm (± 0.18 mm) mean error. With pork loin, error in contact detection was 2.92%, and mean depth error was 7.22 mm (± 1.39 mm).

2.2 Pork samples

All knives were tested on three different meat materials with various characteristics. These were pure muscle tissue (loin), loin with skin and no bones, and belly with skin and no bones. These materials were chosen due to their variation in thickness, homogeneity, and skin presence. Pure loin is a relatively homogeneous tissue with some thickness (about 10 cm) that the knife must work through. Loin with skin has a layer of fat and skin on one side. Skin is more difficult to cut through. The belly is thinner, but has more layers of fat and muscle tissue, in addition to the skin. To test the knives under similar conditions, it was important to keep the variation within each material small, that is, to make the cuts as close to each other as possible.

2.3 Cutting trials

A fixation board, constructed by NMBU, was made from polyethylene with vertical spikes and used to hold the meat in place during the robot cuttings. The parallel tracks prevent the blade tip from touching the board while cutting through the meat. The fixation board with a meat sample attached is shown in Fig. 1d.

One single cut surface per run was decided to be sufficient for taking photos. Hence, all cuts are as close as possible in the material, reducing this source of variation.

The same pieces of meat were cut repeatedly with different tools. The remains were kept in a refrigerator between cuttings. The order of the cuts was decided by the time needed to switch between the knives attached to the robot. This could be between 5-20 minutes and the number of knife exchanges were therefore minimized. The vibrating knife was the most time-consuming to attach to the robot and it was therefore tested first. The design layout, with the order of the cuts is seen in Table 1. The cutting procedure was performed by an initial manual cutting, then a photo was taken within 5 minutes of the cut. The remaining material was cut on the fixation board by the UR10 robot and a photo was taken of the resulting slice. The remaining materials were refrigerated between trials. The procedure was repeated until all three knives were tested with the robot.

Table 1
Design layout of the testing

Run	Operation	Knife	Material
1	Manual	Victorinox	Muscle
2	Robot	Vibrating	Muscle
3	Manual	Victorinox	Loin skin down
4	Robot	Vibrating	Loin skin down
5	Manual	Victorinox	Belly skin down
6	Robot	Vibrating	Belly skin down
7	Robot	Smart	Muscle
8	Robot	Smart	Loin skin down
9	Robot	Smart	Belly skin down
10	Robot	Uddeholm	Muscle
11	Robot	Uddeholm	Loin skin down
12	Robot	Uddeholm	Belly skin down

During testing, the meat samples were positioned in such a way that the fibre direction was similar for all the comparable cuts. They were also repositioned carefully to avoid pinholes from the fixation board during earlier runs. All cutting ran completely through the material, and to measure the effectiveness of each knife, the number of movements needed to cut through the material was counted.

The angle between the fixation board and the knife attached to the robotic arm was fixed throughout the testing. After each cut, the knives were sharpened with an Ergo steel (Cozziniprimedge, Chicago, Illinois, USA) and cleaning wipes were used to reduce the friction which can be caused by residual material on the knife blade.

To keep the temperature as stable as possible, the meat samples were stored in a refrigerator between tests.

In regard to aesthetics, the cuts were photographed in a standardized way using a Sony RX10 II camera. The photos were taken consecutively. The interval between a cut and the preceding photo was less than five minutes with a target of three minutes. Labelled cards were placed next to meat samples during photography.

2.4 Evaluation of manual and robotic cutting

The imagery resulting from the tests was visually compared and scored in a blinded experiment using a panel of assessors. A web-based survey was designed and distributed to project partners and stakeholders with a request of forwarding the open link within their networks. This method of distribution was chosen to ensure respondents with a connection or background to the meat industry. The respondents were anonymous; the only demographics registered were country of residence, in addition a profession category.

An online survey using the Questback platform (Questback; www.questback.com Accessed on 1st August 2021) was chosen as the method of evaluation because of the low development cost, the easy management of the collected quantitative data due to the electronic technology, the capacity to reach more geographic regions, and easy distribution. The survey was designed with comprehensive and specific questions for each sample image (Questback survey: https://response.questback.com/isa/qbv.dll/by-link?p=AGYuoHIBSTxnB-4dJhYppqGHO1Fk5vx-zcA67YqMqK4wOPizPGL5qoCGWs8ZDZ7RMJcWtAN422O1adTg7M2gzA2). A user-friendly design with predefined questions and satisfaction scales is shown to increase participation (Grigoroudis & Siskos, 2010). The survey was introduced with a short description of the project, the rationale behind the survey, and the aim of the study. Guidelines to complete the survey were also given. The images were coded with a three-digit label. The images exemplified in Fig. 2, were assessed by the criteria: even surface, no visible cuts on the surface and no remains of meat, tendons or skin attached to the cut surfaces.

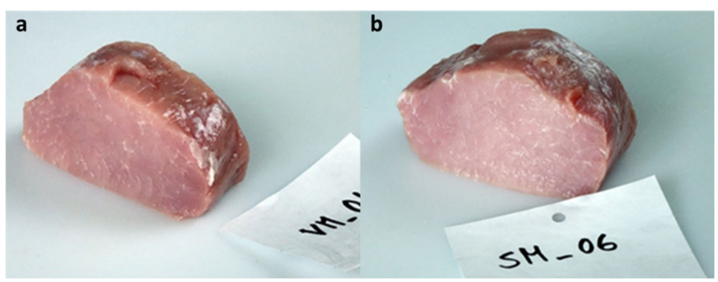

Fig. 2. Muscle tissue cut by the robot armed with (a) the vibrating knife and (b) the Smart knife

A total of 15 images, 5 per material, were presented to the respondents. Two questions were asked for each image: To score the image as either 1 = flawless; 2 = minor flaws, but acceptable for further use and processing; or 3 = unacceptable, and to evaluate whether the slice in the image was cut by 1 = a butcher, 2 = a robot, or 3 = Can't tell. Further commenting on each image was optional.

3. Results and discussion

The survey was open for one month in autumn 2021 and a total of 76 responses were obtained. The responders could choose to state their country of residence but were required to choose a category of profession. Country of residence was important because, as the project is situated in Norway, the researchers could verify the survey response was from an international panel of assessors. The profession categories were added because they provided a means of distinguishing the responders' experience with meat cutting. Some responses lacked "country of residence" which meant the total number of countries represented was at least 15. All profession categories were represented with value "1" representing certified worker in the meat industry (butchery/meat cutting), "2" meaning other work in the meat industry, "3" meaning meat related research and development (e.g., university or institute), "4" representing other research and development professions, and "5" meaning other. This can be seen in Table 2.

Table 2

Respondents in the survey categorized per country of residence and profession. 1 = representing certified worker in the meat industry (butchery/meat cutting), 2 = other work in the meat industry, 3 = meat related research and development (e.g., university or institute), 4 = other research and development professions, and 5 = other

	Profession category					
Country	**1**	**2**	**3**	**4**	**5**	**Total**
Unknown	5		3	5	1	**14**
Czech Republic			1			**1**
Denmark			4		1	**5**
France				1		**1**
Germany			6			**6**
Hungary			2	4	1	**7**
Italy				1		**1**
Norway	3	4	8	6	3	**24**
Serbia			1			**1**
Spain	2	3	1	1		**7**
Sweden				1		**1**
UK		1				**1**
USA			1	1		**2**
Ukraine				3	2	**5**
Total	**10**	**8**	**27**	**23**	**8**	**76**

The results of the survey are shown in Fig. 3. The majority of the respondents accepted most of the samples with the scores 1 and 2. However, as seen in Fig. 3, the vibrating knife which was operated by the robot achieved the highest score, followed by the manually operated Victorinox knife. The Uddeholm and Smart knife operated by the robot, got significantly ($p<0.05$) more "2"- and "3"-scores, indicating a somewhat reduced visual quality of the cuts.

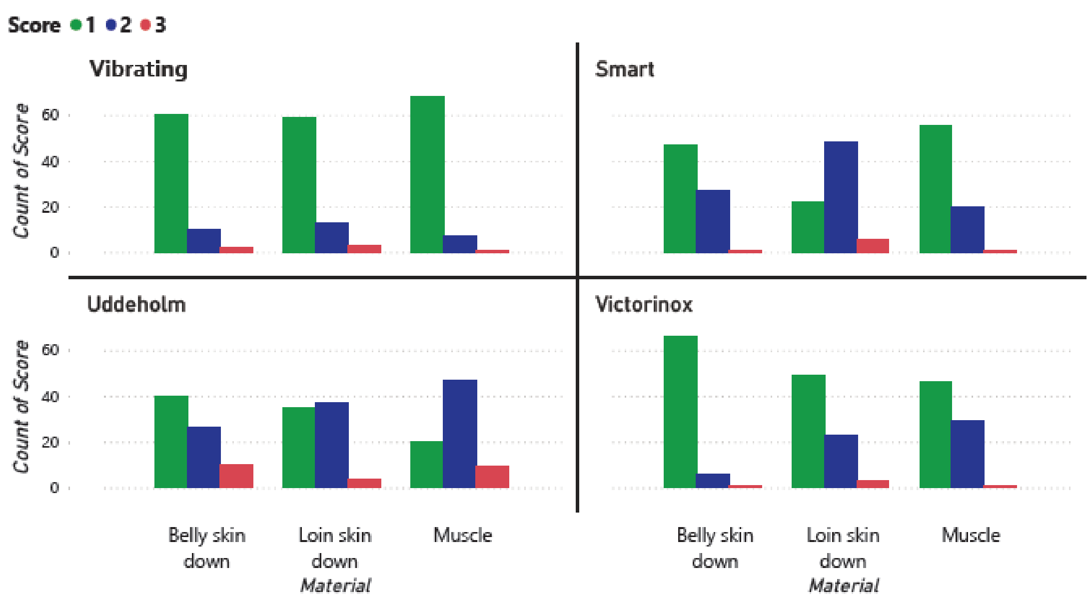

Fig. 3. Respondents' scores on cutting quality of different knives (frames) on various pork samples (horizontal axis). Score 1 = flawless 2 = minor flaws, but acceptable for further use and processing; 3 = unacceptable

In addition to scoring, the respondents were asked whether the cut was made by a human operator or a robot, or if it was impossible to tell. The majority of the respondents were unable to tell if the cut was made by a human or a robot, see Fig. 4. As the Victorinox knife was operated by a human, “1” is the correct response for this knife. The other knives were operated by the robot and “2” is thus the correct response.

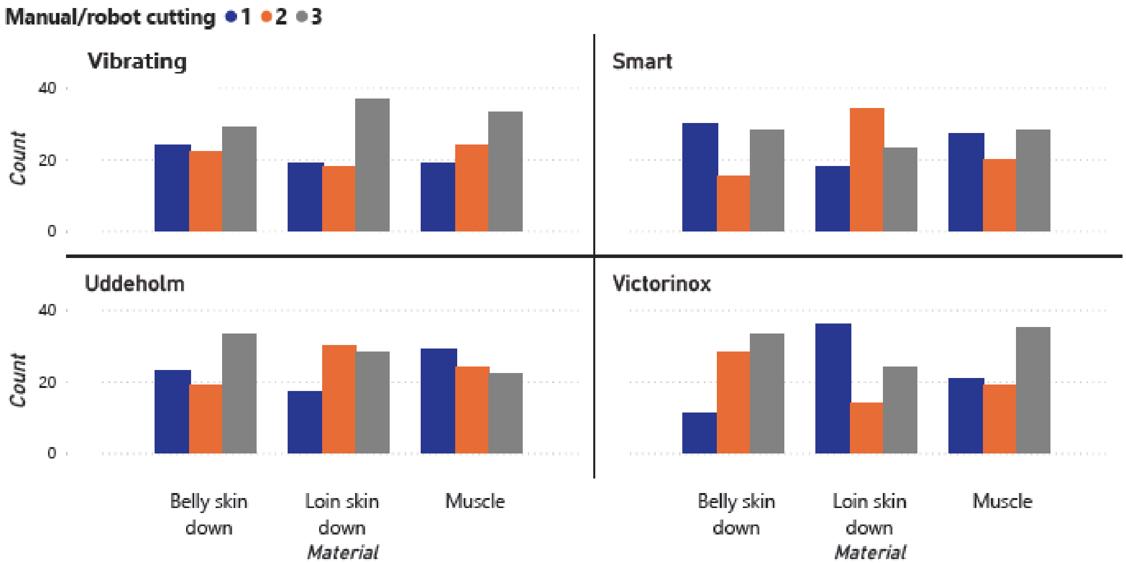

Fig. 4. *Respondents’ classifications on whether various pork cuts (horizontal axis) were made by a professional butcher or a robot. Score 1 = cut by a butcher, 2 = cut by a robot, 3 = can’t tell*

For each of the 76 respondents, the number of correct answers to this question was counted. The correct response value represents the total counts of correct assessed images regarding manual or robot cutting. The Victorinox knife received an average acceptance score of 1.3 with 68 correct responses out of 224 total assessments. The Uddeholm knife received an average acceptance score of 1.68 with 73 correct responses out of 228 total assessments. The vibrating knife received an average acceptance score of 1.19 with 64 correct responses out of 227 total assessments. The Smart knife received an average acceptance score of 1.49 with 69 correct responses out of 227 total assessments.

Assuming a binomial distribution ($n = 12$, $p = 0.5$), a respondent must have 9 or more correct counts to assume significance ($a < 0.05$) – that is; a true ability to separate between robot and manual cuts. Only three respondents achieved 9 counts, hence it is apparent that most could not distinguish between manual and robot cutting.

Regarding efficiency, the vibrating knife was able to cut through all the meat samples in one try. Both the Uddeholm and the smart knives required three cutting movements to completely pierce each of the different materials.

The aim of this study was to assess the quality of fresh meat cuts as a performance indicator of knives specifically adapted for robot-assisted operations. All knives effectively met the aim of being able to cut the test materials with acceptable cut surfaces.

The project’s custom-made knife produced by Uddeholm is well-suited for attachment to the robot arm. The double-edge structure also makes it possible for the robotic arm to cut in two directions. However, it lacks an integrated sensor, or another means for the robot to be able to sense the material which is being cut. It is also a passive knife which means it would require all its power from the robot. In addition, it required several movements to pass completely through the material.

The vibrating knife can be attached to the robotic arm but is not specifically adapted to this purpose and the attachment procedure is therefore time-consuming. The knife has an oscillating motion which makes it cut effectively through the materials. This reduces the force needed to work through materials and allows for accurate cuts through tissue of different densities and consistencies. This makes it possible to cut very thin slices of meat, and to avoid deformation of the tissue due to pressure-free cutting. The fluid cutting motion also reduces adhesion of products to the knife blade.

However, a vibrating knife is best suited for straight cuts and is challenging to conform to more intricate cuts. This makes it less suitable for meat processing where the cutting procedures are more complicated. It is also difficult to attach a sensor to a vibrating knife because the vibrations may interfere with the signals from the sensor. In such cases, the knife may come into contact with bone which means considerable work is required to regrind and reshape the knife blade (Håseth et al., 2020). The need for electric air pressure to operate is also a disadvantage because it complicates the tool exchange for the robot.

The smart knife, in parallel with the Uddeholm knife, is easily attached to the robot. Unlike the Uddeholm knife, it incorporates a sensing system which allows it to cut with improved certainty and precision. This makes it especially suitable as a knife adapted to robot-assisted operations in the meat industry. However, it also required several cuts to pierce the meat samples. This is challenging from a consumer perspective. The sensing abilities of this knife also demand a source of power supply. This can, similarly to the vibrating knife, complicate the tool exchange and be inconvenient in an industry setting.

4. Conclusion

This paper has described a method of testing knives for robotic cutting of meat. The focus of the testing was on evaluation of the quality of the cutting surfaces of meat slices. A panel of assessors with affiliation to the meat industry responded to a survey in which they evaluated images of sample cuts from a market perspective and considered whether the cuts were made by a professional butcher or a robot.

All knives were deemed acceptable in terms of cutting quality. There was also no discernible difference of opinion between manual and robot cuts.

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Author contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by H. R., F. B., P. H. B., and D. R. The first draft of the manuscript was written by H. R. and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Availability of data and material

All data generated or analysed in this study are included in the article's supplementary information materials.

Competing interests

The authors declare they have no relevant financial or non-financial interests.

Statements and Declarations

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