Grasping soft tissue by means of vacuum technique

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Abstract

Introduction. A notable characteristic of bariatric surgery is the frequent manipulation of the bowel. The bowel is large, delicate, flexible, and has a natural lubricant on the tissue surface. Therefore the bowel is difficult to grasp and manipulate. Vacuum technique is commonly used in industry for all types of grasping and manipulation. Two types of nozzles that differed slightly in geometry (NT1 & NT2), were reviewed in an experimental set up for pull tests on pig bowels.

Materials and Method. An experimental set-up was used to conduct a series of pull tests on pig bowel tissue. The basic principle of the measurements was a Newton’s force balance; \( F_{p\ max} = \Delta p * A \). Student t-tests, two-way ANOVA and Wilcoxon signed rank tests were conducted for the statistical analysis of NT1 and NT2 with regard to the maximum pull force \( (F_{p\ max}) \).

Results. Concerning NT1 the Newton’s force balance could not be confirmed. Concerning NT2 the Newton’s force balance could partly be confirmed. For both nozzle types the effect of \( \Delta p \) on \( F_{p\ max} \) was significant. \( F_{p\ max} \) increases linear in proportion as \( \Delta p \) increases. This relation between \( F_{p\ max} \) and \( \Delta p \) was confirmed by the Newton’s force balance.

Discussion. The results confirm that vacuum technique can be used as a grasp technique for soft organs, particularly the bowels. By means of a clever design of the nozzle a firm grip can be obtained on the bowel segments. Therefore vacuum technique should be studied for further development of instruments, graspers and retractors, to be used in the abdominal area.
Introduction

Laparoscopic surgery is a type of minimal invasive surgery where long thin instruments and a scope or camera are used to perform the procedure. The instruments and scope are introduced into the abdominal area through small portholes, so-called trocars. Workspace is created inside the abdominal area by means of carbon dioxide gas.

Since the first laparoscopic removal of the gall bladder in 1985 [1], the number of laparoscopic procedures has increased dramatically. This is especially true for a specific type of laparoscopic surgery called bariatric surgery, also known as weight loss surgery. Bariatric surgery is performed on patients who are dangerously overweight [2]. A notable characteristic of bariatric surgery is the frequent manipulation of the bowel.

The bowel is large, delicate, and flexible, and has a natural lubricant on the tissue surface, making it difficult to grasp and manipulate. Instruments that are used to grasp and manipulate the bowel must provide a firm and safe grip.

Vacuum technique is commonly used in industry for all types of grasping and manipulation. In the medical field, it is a less commonly used grasp and manipulation technique although it is applied in a few applications [3, 4]. A number of studies found in literature also show that vacuum technique has the potential to be used for laparoscopic surgery [5, 6, 7, 8]. In a recent in vivo study where pig bowels were manipulated using
vacuum, the authors showed that this kind of bowel grasping is safe for relatively short manipulations at low and medium high vacuum levels [9].

Two types of nozzles were reviewed in an experimental set up for pull tests on pig bowels. Vacuum force was utilised to grasp the segments of the pig bowels that were used for the pull tests. The aim of this study was to determine the feasibility of vacuum technique for grasping soft organs such as the bowel, and specifically to determine the conditions of a firm grip.
Materials and Method

An experiment was set up to conduct a series of pull tests on pig bowel tissue (Figure 1). It was constructed as follows: a tensile testing machine ((1) Mark 10, US), a vacuum pump ((2) Leybold, Germany), a digital force gauge ((3) Aikoh, Japan), an analogue vacuum control ((4) Carl Roth, Germany), a digitally calibrated vacuum reader (5), and a laptop (6).

(Figure 1)

Among the standard equipment of the tensile testing machine was a set of two mechanical clamps which were used to fixate a specimen. The lower clamp was positioned on the base plate, while an electrical motor allowed the upper clamp, which was attached to the force gauge, to travel up and down at a constant speed. For this study the upper clamp was replaced by a vacuum system (Figure 1). This system consisted of a nozzle (7), a connector (8), a filter (9), and an air tube (10). Two types of nozzle with varying geometrical dimensions were used to grasp the bowel specimens by means of vacuum (Figure 2).

(Figure 2)
The first nozzle type (NT1) was characterised by a cylindrical shape. NT1 had two variable parameters, the inner diameter $D_1$ and the vacuum level $\Delta \rho$. The second nozzle type (NT2) was characterised by the narrowed inlet and had three variable parameters, the inner diameter $D_1$, the inlet diameter $D_2$, and the vacuum level $\Delta \rho$. As the area of focus is minimal invasive surgery, the outer diameter of the nozzle was restricted by the opening of a porthole or trocar, namely a diameter of 12 mm.

The pig bowels were prepared to specimens of 30 cm with 5 cm of mesentery still attached. Physiological salt was used to keep the specimens moist. The bowel specimens were harvested from 20 healthy pigs that had been terminated within the last 12 hours.

Figure 3 shows schematically how the specimens were positioned and fixed in the tensile testing machine. The lower clamp was used to grasp the bowel specimen on the mesentery. The mesentery is a membrane attached to the bowel which connects it to the posterior wall of the abdomen. The specimen was pulled upward at a constant speed (300 mm/min) stretching the specimen until it slipped out of the nozzle. The digital force gauge measured the maximum pull force $F_{p_{\text{max}}}$ which was entered in a laptop computer. The accuracy of the digital force gauge was 0.1 N. Each of the specimens was grasped 5 times by a specific nozzle combination, 5 cm between each grasp. A nozzle combination was determined by $D_1$ and $\Delta \rho$ for NT1 and by $D_1$, $D_2$ and $\Delta \rho$ for NT2 (e.g. NT1: $D_1 = 9$ mm and $\Delta \rho = 60$ kPa; NT2: $D_1 = 10$ mm, $D_2 = 7$ mm and $\Delta \rho = 80$ kPa). $F_{p_{\text{max}}}$ was determined for all nozzle combinations as the mean value of each set of 25 pull tests.
Physical model

The basic principle of the measurements was a Newton’s force balance (Figure 4):

\[ F_{iw} = \Delta p \cdot A \]  

(Figure 3) / (Figure 4)

\( F_{iw} \) represented the force applied to the intestinal wall by the vacuum. \( \Delta p \) was the pressure difference between the vacuum generated by the vacuum pump \( p_{vp} \) and the atmosphere inside the intestinal wall \( p_{i} \). Cross section \( A \) was determined by the inner diameter \( D \) of both nozzles (Figure 2). It was presumed that \( A \) was equal to the surface area of the bowel specimen grasped by the vacuum forces \( F_{iw} \).

The pressure difference \( \Delta p \) acted as a chain linkage between the nozzle and the grasped bowel specimen. The strength of this linkage was determined by a combination of \( \Delta p \) and \( A \) (Figure 4). The measured maximum pull force \( F_{p,max} \), as the force applied to the intestinal wall by the vacuum \( F_{iw} \), therefore depended on \( \Delta p \) and on \( A \). It was expected that the Newton’s force balance that applies to this particular situation could be written as follows:
\[ F_{nw} = \Delta p \cdot A = F_{p\text{max}} \]  

(2).

This meant that \( F_{nw} \) represented the expected outcome of the maximum pull force. Air leakage occurs when the bowel specimen fails to close the inner wall of the nozzle. When this happens, \( \Delta p \) cannot be maintained as a constant and will decrease. As a consequence, \( F_{nw} \) decreases and hence \( F_{p\text{max}} \) also decreases. The narrowed inlet of NT2 was designed to prevent air leakage and allow for a firmer grip on the bowel specimen, compared to NT1. This implied that, according to this model, the pull tests resulted in a significantly larger \( F_{p\text{max}} \) for NT2, compared to NT1.

For nozzle NT1, we varied the vacuum levels and the inner diameter \( D_1 \), and for each combination we obtained 25 measurements of the maximum pull force. Table 1a summarises the possible combinations and lists the corresponding expected maximum pull force based on Newton’s force balance (1).

(Table 1)

For nozzle NT2, we varied the vacuum levels and the inner diameter \( D_1 \) while keeping the inlet diameter \( D_2 \) fixed at 7 mm. For each combination we obtained 25 measurements of the maximum pull force. Table 1b summarises the possible combinations and lists the corresponding expected maximum pull force.
For nozzle NT2, we also varied the vacuum levels and the inlet diameter $D_2$ while keeping the inner diameter $D_1$ fixed at 10 mm. For each combination we obtained 25 measurements of the maximum pull force. Table 1c summarises the possible combinations and lists the corresponding expected maximum pull force. Note that for each variation of $D_2$ at each of the three vacuum levels $\Delta p$, the expected value of $F_{p_{\text{max}}}$ is the same (Table 1c). This is due to the fact that it is $D_1$ that determines $A$ in the Newton’s force balance.

The acquired data was statistically analysed as follows.

A student’s t-test for a mean value was used to evaluate $F_{p_{\text{max}}}$ for each nozzle combination of both nozzle types in relation to the expected outcome of the maximum pull force ($F_{w}$). This test shows to what extent the obtained $F_{p_{\text{max}}}$ deviated from $F_{w}$. The variable parameters $D_1$, $D_2$ and $\Delta p$ were then evaluated within groups of the two nozzle types. The impact of each variable parameter on $F_{p_{\text{max}}}$ in relation to each other for both NT1 and NT2 was statistically determined. A student’s t-test for mean values was conducted to evaluate $D_1$ & $\Delta p$ regarding NT1. A one-way ANOVA was used to evaluate $D_1$, $D_2$ and $\Delta p$ in relation to NT2.

Finally, a two-way ANOVA between groups was performed to evaluate $F_{p_{\text{max}}}$ regarding NT1 and NT2. The two independent variables, or factors, in the ANOVA were defined as nozzle combination and pressure difference.

The level of significance for the t-tests and the two-way ANOVA is $\alpha = 0.05$. Wilcoxon signed rank tests were conducted alongside the t-tests and two-way ANOVA.
Results

Table 2 shows the measured $F_{p_{\text{max}}}$ for NT1 and the corresponding 95% confidence intervals for the different combinations of $D_1$ and $\Delta p$. As can already be seen from the data, the confidence intervals lie above the expected maximum pull force $F_{p_{\text{max}}}$ . For every combination, the average measured $F_{p_{\text{max}}}$ was found to differ significantly from its value obtained from the Newton’s force balance (1).

(Student t-tests yield $p$-values below 0.0001 and the Wilcoxon signed rank tests also give $p$-values below 0.0001.

For the different combinations of $D_1$ and $\Delta p$ of NT1, a one-way ANOVA confirms a clear effect of $\Delta p$ on the maximum pull force $F_{p_{\text{max}}}$ ($ p < 0.0001$). The effect of the inner diameter $D_1$ was found not to be statistically significant ($ p = 0.9182$). An interaction effect between $D_1$ and $\Delta p$ was observed ($ p = 0.0114$).

The results regarding NT2 are as follows. First, $F_{p_{\text{max}}}$ was measured for each combination of $D_1$ and $\Delta p$ while the inlet diameter $D_2$ was kept fixed (Figure 2). The effect of $\Delta p$ is evident ($ p < 0.0001$). Also, the effect of the inner diameter $D_1$ was found
to be highly significant \((p < 0.0001)\), as was the interaction effect between \(D_1\) and \(\Delta p\) \((p < 0.0001)\).

Table 3 shows the measured \(F_{p_{\text{max}}}\) and the 95% confidence intervals for the different combinations of \(D_1\) and \(\Delta p\), together with the expected \(F_{p_{\text{max}}}\). For \(D_1 = 8mm\), all expected outcomes of \(F_{p_{\text{max}}}\) are within the confidence intervals.

Neither student \(t\)-tests nor Wilcoxon signed rank tests indicate any significant differences between the measured outcomes of \(F_{p_{\text{max}}}\) and the expected outcomes.

Regarding \(D_1 = 10mm\), the measured outcomes of \(F_{p_{\text{max}}}\) all differ significantly from their expected outcomes with student \(t\)-test \(p\)-values, varying from \(p = 0.013\) \((\Delta p = 40kPa)\) to \(p < 0.0001\) \((\Delta p = 80kPa)\). The results for \(D_1 = 9mm\) are somewhere between those for \(D_1 = 8mm\) & \(D_1 = 10mm\). For \(D_1 = 9mm\), the student \(t\)-test \(p\)-values vary between \(p = 0.4696\) \((\Delta p = 40kPa)\) and \(p < 0.033\) \((\Delta p = 80kPa)\).

Second, \(D_1\) was kept fixed and \(F_{p_{\text{max}}}\) was measured for each combination of \(D_2\) and \(\Delta p\) (Figure 2). Table 4 shows the measured \(F_{p_{\text{max}}}\) and the 95% confidence intervals for the different combinations of \(D_2\) and \(\Delta p\), together with the expected \(F_{p_{\text{max}}}\).
At all three vacuum levels, the measured $F_{p_{max}}$ decreased for $D_2 = 6mm$ compared to the measured $F_{p_{max}}$ for $D_2 = 7mm$. The main effects of vacuum level $\Delta p$ and inlet diameter $D_2$ were found to be highly significant; no interaction effect was observed.

For all combinations, the difference between the observed average pull force and its expected value on the basis of Newton’s force balance (1) was found to be highly significant.
Discussion

Aim of the study

The aim of the study is to determine the feasibility of vacuum technique as a grasp technique for soft organs. On the one hand this is determined by the grip on the tissue and, on the other, whether the tissue is grasped safely. This study focuses on the grip part of vacuum grasping. The grip was defined as the maximum pull force applicable by means of the tested nozzle types. With regard to grasping the tissue without causing damage, a previously conducted study shows that pig bowels can be grasped safely [9].

Results demonstrated

The first thing to note is that for NT1 the expected pull force cannot be attained, and secondly, that NT2 gets quite close to the expected pull force (Tables 2, 3 and 4). Vacuum grasping seems feasible with regard to NT2, but impossible regarding NT1. The results for NT1 show that the effect of $\Delta p$ on $F_{\text{max}}$ was significant. $F_{\text{max}}$ increases linearly in proportion as $\Delta p$ increases. This relationship between $F_{\text{max}}$ and $\Delta p$ was confirmed by the Newton’s force balance (1) and (2). For $D_1$, the Newton’s force balance cannot be confirmed. The values for $D_1$ ($D_1 = 8, 9, 10 \text{mm}$) that were tested in this study have no effect on $F_{\text{max}}$ in relation to each other. At first sight this is odd, as the dimensional variable $D_1$ determines $A$. $D_1$, according to the Newton’s force balance, should therefore have a positive and proportional effect on $F_{\text{max}}$. The measured $F_{\text{max}}$ for NT1 is twice as low as the expected pull force. This low value of $F_{\text{max}}$ and the non-effectiveness of $D_1$ regarding NT1 are the result of early air leakage when a bowel segment is pulled by means of the nozzle and the tensile testing machine. When the
bowl segment is sucked into the nozzle it sticks to the inner wall due to the vacuum. The bowel segment is then stretched and the tension in the bowel wall pulls the bowel segment of the inner wall of the nozzle (Figure 5). A possible explanation for this event can be described as follows.

(Figure 5)

It is first necessary to describe the bowel in simple terms as if it were a static object. The bowel surface is smooth. It has the shape of a tube and its average diameter and wall thickness are such that tissue folds are caused. There is a membrane attached to the bowel (mesentery) which holds the bowel in position. This membrane was used to position the bowel segment in the tensile testing machine, but without any account being taken with regard to the grip on the bowel. The bowel segment is grasped by the nozzle as illustrated in Figure 2. It is then is stretched and pulled while being grasped by vacuum forces. It is the opinion of the authors that as the bowel segment is being stretched, the bowel characteristics such as the diameter, wall thickness and tissue folds largely determine whether air leakage occurs or not. In other words, the shape and dimensions of the bowel are of great importance. The inside of nozzle NT1 has the shape of a cylinder, which is not sufficient for grasping the bowel segment in line with its dimensions or for closing off the vacuum to achieve the expected pull force. The results for NT2 confirm this phenomenon.
NT2 was specifically designed to prevent air leakage (Figure 2 and 4). The results for NT2 show, similarly to NT1, that the effect of $\Delta p$ on $F_{p_{\text{max}}}$ is significant and $F_{p_{\text{max}}}$ increases linearly in proportion as $\Delta p$ increases. This is obvious, and is due to the same reasons as for NT1. Regarding $D_1$, the Newton’s force balance is largely confirmed (Table 3). The narrowed inlet $D_2$ closes off the vacuum, which allows the expected pull force to be realised. This means that $D_1$, as far as Newton’s force balance is concerned, depends on the performance of $D_2$. When $D_1 = 10 \text{mm}$, the Newton’s force balance is not confirmed (Table 3 and 4). If $D_1$ increases, more tissue is sucked into the nozzle. One explanation is that too much tissue is sucked into the nozzle while the bowel segment has a limited diameter size, resulting in premature air leakage. $D_1$ has an optimum at which the bowel is most firmly grasped. This, however, is an assumption and although it seems probable, it has not been proven.

$D_2$ is an independent variable and as stated, for each variation of $D_2$ at each of the three vacuum levels $\Delta p$, the expected value of $F_{p_{\text{max}}}$ is the same. This is due to the fact that it is $D_1$ that determines $A$ in the Newton’s force balance (Table 4). $D_2$ is not part of equations (1) and (2). Nevertheless, $D_2$ is of great importance as it is the factor that prevents air leakage. Table 4 shows that variations in $D_2$ have an undeniable effect on $F_{p_{\text{max}}}$. However, this effect is not significant with regard to realising the expected maximum pull force.

The effect of $D_2$ can be explained as follows. When the narrowed inlet $D_2$ is not integrated in the nozzle, air leakage occurs and the tissue slips as was shown for NT1. A
relatively large $D_2$ has an effect but it is too small to realise the expected pull force (Table 4). In that case, NT2 shows a closer resemblance to NT1. A relatively small $D_2$ has a negative effect, as the inlet becomes too small for the bowel segment to be sucked into the nozzle. The inlet has a minimum size which still allows the bowel segment to enter the nozzle and a maximum size where the inlet ceases to function. Like $D_1$, $D_2$ has an optimum at which the right amount of tissue is sucked into the nozzle where the tissue can still be sufficiently closed off to prevent air leakage. Tables 3 and 4 confirm this. Choosing exactly the right value for $D_2$ is the criterion that determines whether $D_1$ functions according to the Newton’s force balance — to realise the expected pull force.

It is notable that although NT2 comes fairly close to the Newton’s force balance, the data obtained also show that the results are sometimes close, but not significant. This shows that bowel tissue has varying characteristics and is difficult to model.

Implications

The results confirm that vacuum technique can be used as a grasp technique for soft organs, particularly the bowels. By means of a clever design of the nozzle, a firm grip can be obtained on the bowel segments. Vacuum technique should therefore be studied for further development of instruments, grasper and retractors, to be used in the abdominal area. Organs such as the colon, liver, gall bladder, spleen, and adrenal glands could be subject of further research regarding vacuum grasping [5, 6, 7]. The nozzles that were tested for this study were designed specifically for minimal invasive surgery. Nevertheless, it is conceivable that vacuum technique could also be applied to for general
open surgery and other types of surgery such as single port surgery [10, 11], NOTES [12, 13], and robotic surgery [14, 15, 16].

Correspondence to other literature

The grip on the bowel is at an optimum when the nozzle has just the right dimensions, as explained above. In order to determine the feasibility of vacuum grasping, a nozzle must also be able to exert a pull force of 5 N on the bowel [17, 18]. Tables 3 and 4 confirm that this is possible at a $\Delta p$ of 80 kPa. Three studies found in literature also show that vacuum technique allows for organs to be grasped sufficiently firmly for a period of time without causing any damage [5, 6, 7].

Limitations of the study

The optimum of the nozzle at which a safe grip can be obtained applies only for the type of nozzle used in this study. The results of this study apply to potential applications in minimal invasive surgery. It is likely that the results can be translated to other types of surgery, but this will take more research and study of the subject. Moreover, NT2 can be used on bowels and probably also on the colon. However, for organs with evidently different material characteristics, such as the liver or spleen, NT2 may not be adequate. It seems probable that each type of organ or tissue requires a different type of nozzle.

The bowels used were those of recently terminated pigs. It is clear that dead tissue responds differently to life tissue. If the results are to be translated to the design of a vacuum grasper instrument, it is important to test this instrument thoroughly regarding its
grip and applicable pull force on live pig bowels. In vivo studies concerning vacuum grasping are currently being conducted.

**Conclusion**

The bowels can be firmly and safely grasped by means of vacuum. This offers the opportunity to use a vacuum grasper as an alternative, not a substitute, to the conventional mechanical grasper. The results can be initiated into instrument design. The real optimum is not necessarily one of the tested variations of NT2. The actual optimal dimensions of the nozzle should be determined by further tests, and the results can be the starting point of an instrument design. The nozzle is the element that actually interacts with the grasped tissue and is predetermined by its optimal dimensions. This implies that the design effort should be focused on the control part of the instrument. The control of such an instrument could be either manual or machine-operated.

Further developments concerning the designing and testing of a vacuum instrument, whether manually driven or by vacuum pump, are being conducted to evaluate their feasibility.
Acknowledgements

We would like to acknowledge the assistance and expertise provided by the Skillslab at the Catharina Hospital Eindhoven, the Netherlands, with regard to the experiments conducted.
Figure legends

Figure 1. Experimental set-up

Figure 2. Schematic view of NT1 and NT2

Figure 3. Clamping the bowel

Figure 4. General free body diagram of a nozzle, applies to both nozzles

Table 1, 1a) Expected maximum pull force for nozzle NT1, keeping D2 fixed. 1b) Expected maximum pull force for nozzle NT2, keeping D2 fixed. 1c) Expected maximum pull force for nozzle NT2, keeping D1 fixed.

Table 2. Results of maximum pull force for NT1

Table 3. Results of maximum pull force for NT2 concerning D1

Table 4. Results of maximum pull force for NT2 concerning D2

Figure 5. Occurrence of air leakage (left view), and how to prevent it (right view)
Disclosures

D. Vonck received funding from the Delft University of Technology. P. H. Lopuhaä, J. J. Jakimowicz and R. H. M. Goossens have no conflicts of interest or financial ties to disclose.
References


\[ F_{IW} = \Delta p \cdot A = F_{p_{max}} \]

\[ \Delta p = p_{vp} - p_i \]
Figure 5
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