A Sarong rolled around a body demonstrates that the force for separating two sheets joined by folding and rolling is very large

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Abstract

A lot of new science has been inspired by common phenomena and even by old traditions practiced in our daily lives. Eventually, after deep exploration, this may engender unexpected new technologies. In this paper, inspired by the wearing of a traditional cloth called a sarong, by the community in South East Asian countries and others, we investigate the behavior of sheets folded in the same way as the rolling of the sarong around the stomach. Simple equipment was designed to qualitatively collect the data which was combined with simple modeling. The rolling of the sarong around the stomach generates a joining force between two sheets, increasing proportionally to the square of the number of rolls. This finding can potentially be applied for developing a method for strongly joining sheets by simply rolling them and releasing the join by unrolling. This work can also be simply duplicated elsewhere, so it is worthy of teaching materials at undergraduate level. Both the scientific and the teaching contents can be extracted simultaneously.

Keywords: sarong, folded sheet, cross-folding, side-folding

Supplementary material for this article is available online

1. Introduction

Origami science opens opportunities for the development of technologies in the future by employing very efficient materials. The heart of origami science is the folding of sheets. Today we can see many buildings, the architecture of which has been inspired by origami structure, such as the Festival Hall of the Tiroler...
Currently, scientists are considering a new technology for exploring exoplanets by designing a very large starshade having an origami structure. This umbrella-like module will be placed in space at a distance of about 77,000 km in front of an optical telescope. This module will block the bright light from stars from entering the telescope and only allow dim light from exoplanets orbiting a star. This module must be transported into space at a small size and opened when it reaches the desired position. Using an origami structure, it can be transported in a folded structure and then unfolded after reaching the right position in space [2–5].

Although there has been a lot of research into folded structures, new topics will always appear. It sometimes happens that these new topics are inspired by common phenomena in our daily lives. In this paper, we will investigate the behavior of folded sheets, the folding geometry of which has rarely been reported. This idea was inspired by the traditional cloth in South East Asian countries or others, where many people still use the sarong in their daily lives.

A sarong is made of one sheet of fabric and sewn like an easily-folded cylindrical wall. When worn, the sarong is simply wrapped around the stomach without using any belts or other objects as hooks. It is firmly attached to the stomach after rolling the front part several times. Having been rolled about five times, the sarong can hardly be released by pulling forces. We are going to explore this behavior and expect to identify new physics principles and suggest a potential new mechanism for tightly joining and separating sheets just by rolling and unrolling them.

At first glance, this topic seems very ‘traditional’. But, indeed, there are many ‘traditional’ topics have been explored by other authors that might initiate new technologies. For example, Reis’s group from MIT has investigated many common phenomena in our daily lives, and they have demonstrated many exotic findings [6–11]. Deegan et al investigated the formation of coffee stain rings when coffee drops are dried [12]. Goldberg and O’Reilly described the geometric evolution of cooking spaghetti [13]. The present author has also investigated simple common phenomena such as the bending of fireworks [14], the wringing of wet cloths [15], the rolling of a cylinder containing granules [16, 17], sand tunnel collapse [18], rice winnowing [19], measurement of the atmospheric temperature in an aircraft cabin [20], and bending of vertical sheets that leads to a phase transition [21].

In this work, we designed a simple experiment method so that it can be duplicated elsewhere by teachers of undergraduate students. The experimental tools were made of simple utensils. We believe that this method is worthy of teaching materials in undergraduate courses, especially for schools or universities that are not equipped with the standard research equipment.

2. Experimental details

First, we will estimate the pressure generated in the location between the stomach and the rolled part of the sarong as the rolling number of the sarong is increased. We designed a simple tool as shown in figure 1 by employing the principle of hydrostatic pressure. We used a flexible transparent hose, bent like the letter ‘U’, and filled with colored water. One end of the hose was open and the other end was connected to a toy balloon containing air at 1 atm pressure. Figure 1(b) shows the complete measuring system.

The pressure was measured by firstly rolling the sarong around the stomach. The sequence of rolling the sarong around the stomach is shown in figure 2. Initially, the body enters the sarong’s circumference and then the sarong is stretched to the left and right (a). After that, one edge of the sarong is tightly folded toward the front of the body’s center (stomach) tightly (b) and followed by folding the other edge tightly toward the front of the body. The front part of the sarong is then rolled down several times (d) to obtain a strong, tight wrap (e). The detailed procedure for using a sarong can be seen in the supplementary video (available online at stacks.iop.org/PED/55/065020/mmedia). After making three rolls and reaching the condition where the sarong was wrapped tightly around the stomach, the balloon was then inserted in the position between the sarong and the stomach, causing the water level inside the hose to change. Due
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Figure 1. (a) Measuring the pressure between the stomach and the sarong. A toy balloon is inserted between the stomach and the rolled part of the sarong, resulting in an increase of the air pressure inside the balloon. This then changed the level of water inside the flexible hose. (b) A detailed image of the system used to measure the air pressure inside the balloon.

to breathing, the water level changed constantly. We decided to record the highest difference in the water level. In addition, we assumed that the balloon membrane did not differentiate between the pressure of the air inside the balloon and the pressure between the stomach and the sarong (assuming the balloon membrane is very flexible).

We also measured the frictional forces of the various sheets, for comparison. We measured the force required to horizontally move a stack of sheets that were arranged alternately. The movable sheets were clamped together by a movable clamp. This clamp was attached to a flexible rope passing through a pulley to a load. The fixed sheets were clamped together to a fixed clamp. The sheet stack was placed between two glass plates, each of which had been fixed to a wooden block. A pressure load made of a plastic container, which could be filled with water, was placed above the upper wooden block. This easily permitted a change of mass just by changing the water volume. Figure 3 is an illustration of the measurement tool.

The rope supports a hanging (or ‘forcing’, to force movement of the sheets) load made of a plastic container, that could be filled with water. At each pressure load mass, water is added gently
Figure 2. The sequence of rolling the sarong around the stomach: (a) the body enters the sarong’s circumference and the sarong is stretched to the left and right, (b) one edge is folded tightly toward the body’s center tightly, (c) other edge is folded tightly towards the body’s center tightly, (d) the front part is rolled, and (e) final condition after rolling several times.

into the forcing (hanging) load container. We record the mass of the forcing (hanging) load when the movable clamp starts to move. We used photocopier paper sheets, envelope paper sheets, and a woolen fabric. For the two paper types, we measured up to five movable sheets (until eleven sheets were arranged in the stack), while for the wool fabric we only measured up to four movable sheets (since it is thicker).

In the stack, the bottom and the top sheets were fixed sheets so that the movable sheets only make contact with the fixed sheets, and not with the glass. The inset in figure 3 shows the position of the sheets. The yellow color represents the movable sheets and the violet color represents the fixed sheets. We varied the mass of the load (the total mass including the mass of the upper plate and the wooden block) as follows: 0.75 kg, 1.00 kg, 1.25 kg, and 1.50 kg.

To mimic the rolled part in a sarong that wraps around the stomach, we measured the force required to release folded sheets. We also used the equipment in figure 4. This was different in the arrangement of the sheets between the two glass plates. Instead of using a stack arrangement, we placed a folded sheet between the two fixed sheets. One end of the folded sheet was attached to the movable clamp and the other end was attached to the fixed clamp. The bottom and the top layers are fixed sheets, so that the folded sheet only makes contact with the fixed sheets, and not with the glass, as illustrated in figure 4(a).

The folding geometry is shown in figure 4(b). We generated two types of folding: cross folding and side folding. Figure 4(b) only represents cross folding, without side folding. The cross folding and one side folding are shown in figure 4(c). The sequence from (c1)–(c3) is the process of making one side folding. A double-width sheet is firstly cross-folded, the same as for making a zero side-folding (the same as in figure 4(b) but with double width). This sheet is then side-folded at the center and the final result is shown in figure 4(c). This geometry might be compared to rolling the sarong once. To make a double side fold, we used a triple-width sheet. We repeated the process of (c1)–(c3) by making the side-folding twice.
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Figure 3. Equipment for measuring the frictional force between the sheets in a stack structure. Inset is the arrangement of the sheets under measurement.

Figure 4. (a) The arrangement for measuring the force required to release folded sheets. (b) A sheet with zero side folding. (c1)–(c3) The processes of making sheet having one side-folding.
3. Results and discussion

Figure 5 shows the effect of the number of rolls on the pressure between the rolled part of the sarong and the stomach. The pressure was calculated using the hydrostatic pressure equation \( \Delta P = \rho gh \), with \( \rho = 1000 \text{ kg m}^{-3} \) as the water density (the colored substance did not change the water density since the amount was very small), \( g \) is the acceleration due to gravitation, and \( h \) is the difference in the water level in the hose. We used \( g = 9.77 \text{ m s}^{-2} \), the value for Bandung city, Indonesia, as reported by Khairurrijal et al [22].

We see that the pressure, \( \Delta P \), increased linearly with the rolling number of the sarong, \( n \), with the best fitting of \(^1\)

\[
\Delta P = 0.7n. \tag{1}
\]

This behavior can be explained as follows. We assume that the compression of the stomach surface behaves elastically. By increasing the number of rolls in the sarong from \( n \) to \( n + 1 \), the stomach surface will displace inward by \( \Delta x \). Therefore, an additional elastic force is generated by the stomach to the sarong of \( \Delta F = k\Delta x \), where \( k \) is the spring constant. This relationship leads to the elastic force equation \( F = kx \propto n \).

Again, by assuming the contact area between the sarong and the stomach is nearly unchanged, we obtain \( P = F/A \propto n \), which is consistent with data in figure 5.

From this result, we found that increasing the number of rolls implied an increase in pressure and total contact area. Suppose the initial radius of the roll is \( r_0 \) and the thickness of one rolling layer is \( \Delta x \) (generally it is thicker than the sheet thickness due to slight wrapping). The rate of change of the radius becomes \( \Delta r/\Delta \theta = \Delta x/2\pi \) where \( \theta \) is the rolling angle. Therefore, the radius after rolling by an angle of \( \theta \) is

\[
r = r_0 + \frac{\Delta x}{2\pi} \theta. \tag{2}
\]

When the rolling angle changes by \( d\theta \), the arc length changes by \( ds = r d\theta = (r_0 + (\Delta x/2\pi)\theta) d\theta \). If the effective width of the rolled sarong is \( w_{ef} \), the total contact area after \( n \) complete rolls is

\[
A = \int_0^{2\pi} w_{ef} ds = 2\pi r_0 w_{ef} \left(1 + \frac{\Delta x}{2 r_0} n \right). \tag{3}
\]

The number of rolls is generally less than ten \((n \leq 10)\). The sarong thickness is around one millimeter, while the initial radius might be several centimeters. Therefore, in general, \( n\Delta x/2r_0 << 1 \) and we obtained an approximated area \( A = 2\pi r_0 w_{ef} n \).

The rolling of the sarong increases the pressure and the area, each of which is proportional to the number of rolls. The force that compresses the sarong sheet is \( f = \Delta PA \propto n^2 \). This force plays a role as a normal force in the case of friction between contacting surfaces so that the force required to release the rolled part of the sarong satisfies

\[
F = \mu f \propto \mu n^2 \tag{4}
\]

where \( \mu \) is the ‘friction coefficient’ and might depend on the number of rolls, \( \mu(n) \). In the case of merely touching surfaces, such as a block placed on a surface, the friction coefficient can be considered to be constant. Although, there is also a proposal that even between merely touching surfaces, the friction coefficient might depend on the normal force. For example, Konecny reported that the friction force satisfies \( N^{0.91} \), meaning that \( \mu \propto N^{-0.09} \) where \( N \) is the normal force [23]. We will confirm equation (4) by simple experiments. For this demonstration, we used paper and fabric sheets to show that the behavior applies for sheets generally, instead of for fabrics only.

First, we determine the friction of unfolded sheets. The sheets are arranged in the stack as shown in the inset of figure 3. Figure 6 shows the measurement data for (a) photocopier paper sheets, (b) envelope paper sheets, and (c) woolen fabric sheets. We varied the pressure load placed above the upper glass: 0.75 kg, 1.00 kg, 1.25 kg, and 1.50 kg. The forcing (hanging) load mass is increased gently until the movable clamp (and the attached sheets) starts to move. We found that all the data show a linear increase in the forcing load.

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\(^1\) We did the fitting process by using the instruction Add Trendline in Excel by fixing Set Intercept = 0. We did this procedure based on the fact that the pressure should be zero when the rolling is zero.
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\[ \Delta P = \rho gh \]  [kPa]

when the number of sheets increases.\(^2\) We also observed that the slope increased with an increase of the pressing mass.

The contact area is proportional to the number of sheets, or \( A \propto n \). From all the data, we can deduce a relationship between the forcing load, \( W \), and the number of sheets as

\[ W = \Omega(M_p)n \]  \hfill (5)

where \( \Omega(M_p) \) is a factor which depends on the pressing mass, \( M_p \). Based on all the data in figure 6, it is very clear that \( \Omega(M_p) \) increases with \( M_p \). Our next objective is to determine the dependence of \( \Omega(M_p) \) on \( M_p \).

In equation (5), \( \Omega(M_p) \) is the slope of the curve of \( W \) versus \( n \). To determine the dependence of \( \Omega(M_p) \) on \( M_p \), we plot \( \Omega(M_p) \) against \( M_p \) and then search for the fitting curve. \( \Omega(M_p) \) was obtained from the fitting curves in figure 6. For the photocopier paper sheets and the envelope paper sheets, we identified that \( \Omega(M_p) = cM_p \) where \( c \) is a constant. However, for the woolen fabric sheets, we obtained \( \Omega(M_p) = c_1M_p + c_2 \) where \( c_1 \) and \( c_2 \) are constants. This difference is possibly caused by the fact that the woolen fabric is much thicker than the paper sheets and the fabric sheet is sometimes not perfectly flat. In addition, the wool fabric surface is likely to be hairy. Based on this evidence, we may claim that for smooth sheets, the relationship \( \Omega(M_p) = cM_p \) is satisfied. Combining with equation (5) we then obtain

\[ W = cM_p n. \]  \hfill (6)

Now let us investigate the effect of side-folding on the forcing load. This side-folding mimics the roll of the sarong. We measured the effect for the photocopier paper sheets and the envelope paper sheets. Figure 7(a) is the data for the photocopier paper sheets and (b) is the data for envelope paper sheets. We fixed the pressing load mass at 1.50 kg.

If we plot the results using a linear scale, we obtain nonlinear curves. Therefore, we tried a different scale to obtain a linear change. We identified that a linear change was obtained if we plot the load against the square of the number of side-folds. Surprisingly, the slopes of the

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\(^2\) We did the fitting process by using the instruction Add Trendline in Excel by fixing Set Intercept = 0. We did this procedure based on the fact that the load must be zero when there is no movable sheet to pull.
Figure 6. The effect of the number of movable sheets on the load. We tried three kinds of sheets: (a) photocopier paper sheets, (b) envelope paper sheets, and (c) woolen fabric. Four pressing masses were applied to each sheet: 0.75 kg, 1.00 kg, 1.25 kg, and 1.50 kg.

By comparing equations (4) and (7), we obtain the friction coefficient changes according to $\mu \propto (1 + \gamma/n^2)$ where $\gamma$ is a constant. At this point, we can claim that the force required to release the sarong is identical to the force for releasing the folded sheets and it increases according to the square of the rolling number.

We observed the loads required to release the sheet stack are different from the loads required to release the side-folded sheets. The latter force increased more rapidly than the previous one. This is caused by the creation of the folded edges. There are two folded edges created: the cross-folding edge and the side-folding edge. For zero side-folding, as shown in figure 4(b), only a cross-folding edge exists. However, for a geometry containing side-folding, a side-folding edge is also generated.

To create a folded edge, we need a certain force. This is similar to the force required for producing a crease [24–26]. Moving the folded sheet is identical to generating a new crease, so that a comparison between the additional force required and the one in a moving sheet without folding edges (as in the stack structure) is required. Edler et al described that the force required to fold a film scales as $F \propto bB/H^2$, where $b$ is the width of the film, $H$ is the size of the gap between the two films after folding, and $B$ is the bending modulus [27].

Finally, we investigated the effect of the width of the folded paper sheet (photocopier paper) on the forcing load. We changed the width from 0.01 to 0.07 m without side-folding (inset (a) in the figure). The results are the square symbols shown in figure 8. The load increased with the width of the sheet. Fitting the data with a linear curve, we obtain a function $W = 23.4t + 1.026$ (kg). This equation might be less accurate for very small widths since it must be the case that $W \rightarrow 0$ as $t \rightarrow 0$. The curve predicts that the load becomes $W = 3.366$ kg when the sheet width becomes 0.1 m (point A in the figure).

We also investigated the effect of asymmetrical folding size on the forcing load. Paper sheets of 0.1 m width were folded at different width ratios: 2.5/7.5, 4/6, and 5/5. Inset b in figure 8 is a description of the folding geometry. The circle symbols in figure 8 give the measured results. Fitting the data with a linear function resulted in an approximated equation $W = 0.37(t_1/t_2) + 3.255$.
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**Figure 7.** The effect of the squared number of side-folds on the load required to start the movement of the sheets: (square) for the envelope paper sheets and (circle) for the photocopier paper sheets. The symbols are the measured data and the lines are the linear fitting curves. The pressure load was fixed at 1.50 kg.

**Figure 8.** The measured data (circles) on the effect of the folded paper width on the load (the paper was not side folded). The geometry is shown in inset (a). The effect (squares) of asymmetric side folding width on the load. The geometry is shown in inset (b). In both experiments, the pressure load was 1.50 kg.
It is clear that the dependence of the load on the ratio of \( t_1/t_2 \) is very weak. One interesting result is when \( t_1 = 0 \) or \( t_1/t_2 = 0 \) we have the curve crossing the load axis at 3.255 kg (see point B in figure 8).

Indeed, points A and B in figure 8 represent the same condition. Point A is obtained when the width of the sheet (without side folding) is 0.1 m. Point B is the condition where \( t_1 = 0 \) and \( t_2 = 0.1 \) m (the condition of no folding). Therefore, both points are identical and have been obtained from the extrapolation of two different measurements. Their values are nearly identical (3.366 kg for point A and 3.255 kg for point B).

### 4. Conclusion

We have been able to design a simple tool for extracting the mechanical behavior of wearing the traditional cloth, called a sarong, by rolling the cloth around the stomach. The rolling generates very high joining forces that increase with the square of the number of rolls. This type of joining is very interesting since we do not need a belt or another type of hooked object. The data collected from the experiment using paper sheets and woolen fabric sheets were consistent with a simple model. This topic sounds very simple, but it was possible to prove that even common phenomena around us can generate new science and new technology.

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### References

[1] Architizer Editors Folding architecture: top 10 origami-inspired buildings (https://architizer.com) (Accessed: 26 May 2020)

[2] Carter J 2019 A giant origami space telescope that can photograph alien worlds: is this NASA’s next flagship mission? Forbes

[3] Amos J 2017 James Webb: telescope’s giant origami shield takes shape (https://www.bbc.com/) (Accessed: 26 May 2020)

[4] Wilson L, Pellegrino S and Danner R Origami sunshield concepts for space telescope (www.its.caltech.edu/~sslab/PUBLICATIONS) (Accessed: 26 May 2020)

[5] Miura K 1980 Method of packaging and deployment of large membranes in space 31st IAF Congress (Tokyo, Japan)

[6] Miller J T, Lazarus A, Audoly B and Reis P M 2014 Phys. Rev. Lett. 112 068103

[7] Akono A-T, Reis P M and Ulm F-J 2011 Phys. Rev. Lett. 106 204302

[8] Vandeparre V, Pineirua M, Brau F, Roman B, Bico J, Gay C, Bao W, Lau C N, Reis P M and Damman P 2011 Phys. Rev. Lett. 106 224301

[9] Buchak P, Eloy C and Reis P M 2010 Phys. Rev. Lett. 105 194301

[10] Raux P S, Reis P M, Bush J W M and Clanet C 2010 Phys. Rev. Lett. 105 044301

[11] Lee A, Brun P-T, Marchlot J, Balestra G, Gallaire F and Reis P M 2016 Nat. Commun. 7 11155

[12] Deegan R D, Bakajin O, Dupon T F, Huber G, Nagel S R and Witten T A 1997 Nature 389 827–9

[13] Goldberg N N and O’Reilly O M 2020 Phys. Rev. E 101 013001

[14] Abdullah M, Khairunnisa S and Akbar F 2014 Eur. J. Phys. 35 035019

[15] Rahmayanti H D, Utami F D and Abdullah M 2016 Eur. J. Phys. 37 065806

[16] Wibowo E, Rokhmat M, Sutisna , Yuliza E, Khairurrijal and Abdullah M 2016 Powder Technol. 301 44–57

[17] Yuliza E, Amalia N, Rahmayanti H D, Munir R, Munir M M, Khairurrijal K and Abdullah M 2018 Powder Technol. 336 506–15

[18] Yuliza E, Amalia N, Rahmayanti H D, Munir R, Munir M M, Khairurrijal K and Abdullah M 2018 Granular Matter 20 75

[19] Munir R, Rahmayanti H D, Murniati R, Rahman D Y, Utami F D, Viridi S and Abdullah M 2020 Granular Matter 22 24

[20] Sinebar W and Abdullah M 2018 Phys. Teach. 56 556
A Sarong rolled around a body demonstrates

[21] Margaretta D O, Amalia N, Utami F D, Viridi S and Abdullah M 2019 *J. Taibah Univ. Sci.* **13** 1128–36
[22] Khairurrijal, Widiatmoko E, Srigutomo W and Kurniasih N 2012 *Phys. Educ.* **47** 709
[23] Konecny V 1973 *Am. J. Phys.* **41** 588
[24] Coffin D G et al 2018 Advances in pulp and paper research *Trans. 26th Fundamental Research Symp.* (Oxford: Pulp and Paper Fundamental Research Society) pp 69–136
[25] Nygårds M, Just M and Tryding J 2009 *Int. J. Solids Struct.* **46** 2493–505
[26] Beex L A A and Peerlings R H J 2009 *Int. J. Solids Struct.* **46** 4192–207
[27] Elder T, Rozairo D and Croll A B 2019 *Macromolecules* **52** 690–9

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