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Free Tendons for Travelling Wave generation in Elastomer Membranes

Peter Wharton¹, Hermes Bloomfield-Gadêlha² and Andrew T. Conn³

Abstract—A novel method for the generation of travelling waves in soft robots is presented. Here a soft elastomer membrane is embedded with freely sliding nylon tendons. Instead of being anchored to a point on the membrane, these tendons transmit force via friction generated by sliding within the interior of the membrane. This system can produce continuous travelling waves with amplitudes of 27-45mm at wave speeds of up to 23mm/s, using only a single actuator to apply tension to the tendons. The travelling waves were able to move granular material (poppy seeds) as well as a 147g apple. Experimental results demonstrate that the wave progresses through three phases; the initial static phase, followed by the travelling wave phase and finally the (end of travel) blocked phase, with curvature increasing and wave amplitude decreasing across the travelling and blocked phases. This represents wave degradation in which the membrane compresses relative to the tendon, though this did not limit wave travel over the displacements tested. The wave speeds produced were an order of magnitude higher than tendon winding speed suggesting the system acts with natural gearing. This mechanism shows promise for applications in matter transport of unstructured or soft objects and the principle could also be applied to locomoting robots as the low amount of actuators and degrees of control would reduce the complexity and bulkiness of the robots.

I. INTRODUCTION

Soft robots show great promise for applications where adaptability is more desirable than precision. The ability to conform to unpredictable and varying environments is invaluable for tackling problems outside of highly controlled environments. The high degree of compliance is more typical of biological organisms which are very well adapted to moving through and interacting with an unstructured environment. One of the methods by which they achieve this is by producing travelling waves, which are ubiquitous in nature. They form the locomotion system of many organisms, including worms, snakes, snails, many sea creatures as well as microscopic organisms such as bacteria. Travelling waves are also central to the swimming of sperm and is thus vital to reproductive function for most animals. Another common usage is for matter transport, for example peristaltic waves within the human digestive system to transport waste or ciliated epithelial cells which transport mucus. Because of this biological precedent many efforts have gone into making

travelling wave mechanisms in robots, particularly within the soft or bio-inspired robotics fields [1] [2] [3] [4].

Conventional approaches to generating travelling waves utilise a number of discrete units attached in series, which are actuated in sequence. However, with this approach the number of units required scales poorly with fidelity of the wave and its travel length. Depending on the design of the system, achieving a smooth continuous wave can necessitate a large number of actuators and degrees of control, thus making systems more complex and less compact. Some systems avoid this scaling however; one approach uses soft digital logic units to transfer the pressure signal through sequential pneumatic elements [5], these logic units can be connected to form a ring oscillator [6] while another approach uses DEs (dielectric elastomers) as both actuators and switches to generate a self-oscillating system which is demonstrated in a caterpillar robot [7].

Fig. 1. The figure shows a proof of concept for a matter transport system which can transport granular and large objects. From left to right; 6g of poppy seeds, a 71g orange and a 147g apple. The white arrow indicates wave travel direction. The wave is reset by stretching the membrane back out flat and forming another ruck.

Alternatively, some mechanisms achieve a continuous travelling wave without using a sequence of active units. This can be achieved by leveraging fluid resistance by introducing an open cell sponge into pneumatic chambers to delay the pressure signal [8]. Another approach utilises the buckling of thin bands on the outer surface of a cylindrical worm robot to produce travelling waves [9].

The solution presented in this work utilises a 'ruck' in a sheet of silicone to produce a travelling wave. Rucks are localised buckled regions where the membrane is not in contact with the surface [10]. Static friction and the length of the rig prevents the edges of the membrane from slipping and the ruck dissipating. We embed tendons within an elastomer membrane such that they reside in plane with the membrane

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at a mid-point in its thickness. Applying a longitudinal tensile force to the tendons breaks them free from any bonding to the membrane, which effectively creates their own internal channels to slide through (further details of the fabrication process are given in Section II-C). The tendons are considered free as they are not anchored at any point on the membrane as with traditional robotic tendons, but instead slide relative to the membrane and transmit force via sliding friction. When tension is applied to the tendons across a pre-existing ruck, the ruck is dynamically projected across the membrane, thus generating a singleton travelling wave with only one actuator. This wave is capable of transporting granular matter as well as large objects (Figure 1). In this paper, we will first explain the principle of operation of the wave membrane mechanism, before going onto the system design and experimental methodologies in Section II. The results are presented in Section III, and then discussed in Section IV, with conclusions following in Section V.

II. DESIGN, OPERATION & METHODS

A. Principle of Operation

The main component of the system is the wave membrane: a sheet of silicone with parallel free tendons embedded longitudinally within it. Applying tension to these tendons causes them to slide within the membrane and the membrane to compress longitudinally which results in a non-uniform frictional force which propels pre-existing rucks down the membrane.

Ruck: The ruck is a region of the membrane which is raised above the surface in a buckled shape [10] [11], the friction between the membrane and the surface it lies on prevent its dissipation. In this study the ruck is propelled across the membrane by forces applied by the free tendons as shown in Figure 2. The static shape of rucks and the dynamics of their formation and translation has been the subject of several theoretical studies. This includes work by Vella et al [10] who determined that larger rucks move slower than smaller ones and that the effective tension in the membrane reduces with increasing ruck height. Kolinski et al [11] analysed the excess length of the rucks are relative to its horizontal base and found that a critical value of this parameter exists, above which the ruck loses symmetry and tilts to one side.

Free Tendons: Traditionally, robotic tendons are fixed (or anchored) on at least one point on a structure and tension is transferred to the anchored point(s) from an actuator. Here the tendons are cast within the membrane itself. When tension is applied to the tendons, any bonding with the membrane is broken so that they can slide through the membrane within the internal void created by the tendons initial position. A distributed force along the tendons length is generated by friction between the tendon and the inside of the membrane as it slides.

Ruck motion: When tension is applied across the tendons in the ruck region of the membrane, an orthogonal force F_p is transmitted to the membrane as the tendon moves to straighten (see Figure 2 and Figure 3). F_p pulls downwards

Fig. 2. A diagram of wave membrane operation. a) Shows the initial state of the membrane before ruck creation. b) Shows the creation of the ruck by applying a force from the left causing the membrane to buckle. c) Shows the motion of the ruck when tension is applied along the thread. Here v is the sliding speed of the tendon within the membrane (caused by the motor), which decreases over the ruck due to longitudinal compression of the membrane. F_m is the friction force between the tendon and the membrane which opposes tendon tension F_t . F_p represents the force applied by the tendon on the membrane as F_t causes it to straighten. F_p is weaker on the trailing side of the ruck thus breaking symmetry and causes ruck motion towards the receiving end at speed c .

on the (positive curvature) peak of the ruck and pushes outwards on the (negative curvature) slopes of the ruck. As the tendons are reeled in, longitudinal compression of the membrane around the tendons takes place, as well as a reduction in ruck size. As a result less force is transmitted to the trailing edge of the ruck and the asymmetry in F_p drives the ruck forwards.

Fig. 3. The straightening forces of the tendons are visible during operation. The near side tendon is highlighted in cyan. (1) Shows the ruck before tension is applied. (2) The ruck driven into motion by tension in the tendons (arrow indicates direction of wave travel). (3) Shows the extreme end state in which the tendon becomes nearly straight with the membrane heavily warped around it.

B. Design

In this study a rectangular wave membrane 180x70x2.5mm in size and composed of Ecoflex 00-30 (Smooth-On) is used. The tendons are two nylon threads embedded longitudinally within the membrane, spaced at 1/3 and 2/3 of the membrane width (increments of 23.3mm) and halfway through the thickness (1.25mm from the top and bottom surfaces). The membrane is fixed in place at either end of the system (Figure 4), the (rear) emitting side fixing is an adjustable sliding attachment point, allowing the creation and dispersion of rucks of varying size within the membrane. It can also disperse smaller, inhomogeneous deformations of the membrane by stretching the membrane longitudinally. The sliding mechanism has three separate pieces; the base piece slides in grooves on the main aluminium base, the top piece screws on to the base and holds the membrane via friction and a 4mm diameter steel

bar which ensures the membrane buckles from the base surface rather than upwards out of the adjustable attachment point (Figure 4). Friction between the sliding mechanism and the main base keep its position fixed during operation. In a practical application the sliding mechanism could make the system self reset using only one additional actuator.

The tendons are attached to a 4mm diameter steel axle which is connected through a 1:3.6 gear chain to a Pololu 6V MP Micro Metal DC motor with a gearing ratio of 298:1 and attached magnetic encoders with 12 counts per rotation. The motor has a no load speed of 73RPM and a stall torque of 2.4kgcm. The threads at the emitting side are fixed to the adjustable slider (though rate of thread travel here is usually zero until resetting the system). The motors are controlled by an Arduino Uno board with a H-bridge dual channel motor driver.

Fig. 4. The wave membrane system. The wave travels from the emitting side to the receiving side at speed c (indicated by the white arrow).

C. Fabrication

The wave membrane is a flat rectangular sheet of silicone of size 180x70x2.5mm with two lengthwise embedded tendons (nylon waxed thread 1mm diameter). The elastomer is drop cast using a rectangular shell PLA mold with wall thickness 2mm. The nylon threads are suspended within the mold using 0.7mm thick notches cut into the edge of the mold. The silicone elastomer is poured into the mold (over the threads) so the threads remain embedded within the elastomer after it cures. There is also a narrow PLA (5x3x180mm) block placed on one long edge and removed after curing, leaving a gap of 5mm into which red dyed elastomer is poured. The red coloured edge of the membrane assists in computer vision tracking of the membrane. The membrane is cast with Ecoflex 00-30 (Smooth-On), but other elastomers were found to produce qualitatively similar responses yet with different magnitudes. For example, using a stiffer elastomer increases the size of the ruck that will form for a given length compression. The sliding mechanism, end block pieces, motor and axle attachment pieces are all 3D printed PLA with 100% infill and attached with m3 screws or superglue. The base is machined from aluminium.

D. Methods

Here the experimental methodology used in this study is outlined. The objective is to track the motion of the

membrane over a range of initial amplitudes and a range of surface friction values to explore a 2D curvature response.

The three surface materials used in the experiments, listed in order of decreasing friction are; 1) the aluminium base, 2) regular printer paper affixed onto this base, 3) cornflour used as a dry lubricant between the aluminium base and underside of membrane. The static friction coefficients with the membrane for each surface material are shown in Table I, these were obtained using the angled plane sliding test.

The different sized initial waves are a product of moving the rear adjustable fixing inwards, thus buckling the membrane upwards at the emitting end. The three different initial wave sizes used in this study represent inwards slider displacements of 10mm, 25mm and 40mm, which corresponds to a compression of the sheet length by 6.5%, 16.1% and 25.8% respectively. For each variation of the experiment 5 trials were carried out and in each the DC motor was ran for 10 seconds at a constant 4V, applying tension and winding in the embedded tendons. Between each trial the membrane and initial ruck position are manually reset.

Surface	Coefficient of Friction with membrane
Aluminium	1.50 ± 0.08
Paper	1.00 ± 0.05
Cornflour Aluminium	0.48 ± 0.05

TABLE I

STATIC FRICTION MEASUREMENTS FOR THE SURFACES USED DURING TESTING. AVERAGE AND STANDARD DEVIATION SHOWN FROM 10 MEASUREMENTS.

The system was placed within a 60cm³ photography light box with two bright LED lamps- this created a consistent high lighting level regardless of the ambient light conditions, facilitating more reliable tracking of the red dyed edge of the membrane. The camera was positioned in a 3D printed (PLA) frame at a fixed distance of 200mm from the base. The data was analysed within MatlabR2020a, where first HSV filtering was used to return the red pixels then a sequence of thinning and filtering processes to eliminate noise were used to find an x,y sequence corresponding to the detected red edge of the curve. The motor rotation and angular velocity were directly measured using the encoders. The motor torque was calculated using the torque-speed relationship at a constant voltage taken from the motor's datasheet [12]. We tracked the side edge of the membrane during these experiments. It is noted that this does not capture the deformation of the membrane along the axis perpendicular to the waves motion. The membrane does however maintain a relatively constant cross section for most of the duration of the trial, however, which supports the validity of this approximation. The tracked edge of the membrane is 160mm long, as 10mm of the membrane on each side is used to clamp to the end fixings.

III. RESULTS

Here we present and analyse the results obtained from tracking the wave membrane with variable ruck initial size

and the surface friction. Figures (5, 6, 7) show the time evolution of the curvature of the wave membrane when tension is applied to the tendons. The curvature here is calculated by tracking the change in the inclination of the tangent angle of the membrane over the entire arc for each time step, so it can then be represented by colour in a time-displacement plot. Note that displacement here refers to distance along the membrane curve, not the horizontal spatial axis. In these plots, the yellow bands represent regions of high positive curvature which correspond to peaks in the membrane, whilst the blue areas represent negative curvature which is found on the leading and trailing edges of the ruck (green represents flat areas of the membrane).

For all cases except the cornflour lubricated surface with a small amplitude initial ruck, travelling wave behaviour was observed, which is represented by the diagonal direction of the yellow band typically between $t=2s$ and $t=5s$ (see Figures 5, 6, 7) with the exception of (Figure 7a). The peak of the ruck (defined as the point of maximum positive curvature) travels approximately 50% of the length of the membrane (80mm) and is bounded by the membrane being constrained at the receiving and emitting ends. In contrast with the other examples the cornflour lubricated surface with small amplitude ruck shows a discontinuity in the yellow band (Figure 7a) indicating that the ruck dissipated and reappeared at the emitting end between $t=3s$ and $t=4s$.

Fig. 5. The curvature plots and example visualisations for all trials on the aluminium base, static friction coefficient= 1.50 ± 0.08 . (a) Shows an average of small initial ruck runs, (b) average of medium initial rucks and (c) average of large initial rucks. A visual progression is shown from a side on perspective underneath, with the line colour again representing the curvature of the membrane edge. The curvature heatmap values are bounded by $\kappa_{max} = 0.128\text{Rad/mm}$ and $\kappa_{min} = -0.128\text{Rad/mm}$. A black curve shows the initial ruck position.

The wave speed and the speed of the thread winding over the course of a trial were taken (see Figure 8). The wave speed was defined as the rate of travel of the point of maximum curvature along the membrane whilst the thread winding speed was directly measured using an integrated encoder. The tendon winding speed for medium and large amplitudes maintained a constant 2.5mm/s. The small amplitude speed began similarly, but rapidly decreased at around $t=5s$. Wave speed does not appear to reach a constant value during these trials except for the small initial amplitude trials for a brief period. Instead it increased to a peak then decreased to a slow, but non-zero speed which gradually

Fig. 6. The curvature plots and example visualisations for trials on paper surface, with reduced static friction compared to the aluminium base, static friction coefficient= 1.00 ± 0.05 . The curvature heatmap values are bounded by $\kappa_{max} = 0.128\text{Rad/mm}$ and $\kappa_{min} = -0.128\text{Rad/mm}$ and the black curve shows the initial ruck position. (a) Shows an average of small initial ruck runs, (b) average of medium initial rucks and (c) average of large initial rucks.

Fig. 7. The curvature plots and example visualisations for trials on cornflour lubricated aluminium surface, with reduced static friction compared to the aluminium base, static friction coefficient= 0.48 ± 0.05 . The curvature heatmap values are bounded by $\kappa_{max} = 0.128\text{Rad/mm}$ and $\kappa_{min} = -0.128\text{Rad/mm}$ and the black curve shows the initial ruck position. (a) Shows an average of small initial ruck runs, (b) average of medium initial rucks and (c) average of large initial rucks.

reduced to zero over the last 4 seconds. The slow final phase represents the increasing curvature moving the wave peak slightly further down the membrane, even if the progress of the ruck itself is halted.

The maximum wave height (Figure 9) and the maximum curvature of the wave (Figure 10) were measured as a function of time and compared across the different initial ruck sizes. The maximum height of the wave is measured by taking the highest vertical position and subtracting it from the base height, this measurement can lose accuracy in later stages of a trial when the ruck tilts towards the receiving end as the highest point in absolute terms may not correspond to the peak of the ruck and in any case the amplitude of the ruck becomes difficult to define due to the tilt. In Figure 9, we see a general trend of decreasing peak amplitude through time with noticeable levelling out towards the end of the run. The end height as a percentage of initial height is 65% for large 70% for medium and 71% for small.

The maximum curvature data (Figure 10) shows almost the exact reverse trend of the peak amplitude data (Figure 9), with steady increases up to 154% of initial value for large and 142% for medium and small. Both plots show a small

Fig. 8. The wave speed and tendon speed as a function of time and averaged across small, medium and large initial rucks

initial fluctuation counter to the primary trend direction at around $t=3$, with the exception of the wave height for small initial wave amplitudes.

Fig. 9. Amplitude modulation of travelling waves as a function of time, averaged across initial wave amplitude

Figure 11 shows the tendon displacement and the tendon tension as a function of time summarised over the three initial ruck amplitudes. We see that the tendon displacement follows a consistent linear trend with only the small amplitude cases deviating late during the runs. The tendon tension remains fairly constant at around 5N again with the exception of the small amplitude case which sees a significant spike to over 10N towards the end of the trials.

IV. DISCUSSION

The wave behaviour can be split into three phases; 1) involves an initial period of zero ruck movement, followed by 2) which is the motion of the ruck from it's initial position on the emitting side over to the receiving side, this is the travelling phase, finally 3) occurs when the ruck becomes blocked at the receiving side and can no longer travel- the blocked phase. This can be seen in (Figures 5, 6, 7) by tracing the yellow band. Vertical sections of this represent

Fig. 10. Maximum ruck curvature shown as a function of time, averaged across small, medium and large initial wave amplitude

Fig. 11. Motor displacement (amount of thread wind in) and tension on thread as a function of time. Averaged across all small, medium and large ruck trials.

the stationary initial and final phases whilst the travelling phase is the diagonal connection between them.

During the travelling phase, the internal sliding friction instigated by the tendons propagate the ruck along the membrane. Despite the intrinsic non-linearities of the system, the wave travels with approximately constant speed in the travelling phase, as can be seen in (Figures 5, 6, 7). Nevertheless, boundary conditions modulate both the wave amplitude and wave speed, which decay in time- despite the imposed constant winding speed of the tendons. The initial ruck shape defines the stability and appearance of subsequent modes and suppresses the pitchfork bistability inflicting classical elastica systems [13] [14].

When the system enters the blocked phase, the ruck cannot travel further down membrane, however the peak curvature continues to increase (Figure 10) and the ruck tilts towards the direction of pull. This can be observed as an intensifying of the colour in the lower-right corner of the curvature plots or seen more directly in the below visualisations (Figures 5, 6, 7). Warping of the membrane which is not captured in this data also became significant during this phase.

We can infer that the motor encounters resistance towards

the end of the small initial ruck trials due to a significant spike in force (Figure 11) and corresponding drop off in tendon winding rate (Figure 8). This is due to the tendon becoming almost totally straight and pulling directly against the fixing at the emitting side. This is a limitation in wave travel distance for this system, as once the tendon stops moving there is no asymmetry caused by the winding direction to create motion. The ruck shape is also crushed flat (Figure 3). Medium and large ruck sizes maintain a relatively constant tendon tension and rate of tendon winding which indicates constant and equal tendon sliding resistance in both cases. There is a slight drop-off that can be detected at the end for the medium case though, which may indicate the tendons are beginning to straighten out. There may be a positive correlation between ruck size and maximum travel distance due to more winding being required to straighten the tendon in larger rucks. It is notable that the peak wave speed is an order of magnitude faster than the thread winding speed, and only about 25mm of tendon travel is required for an entire trial (much of which happens in the blocked phase and does not contribute to ruck motion). It is possible to view the system as geared- inducing a large motion with lower force from the slower, high force tendon motion. This opens up potential for integration of other driving mechanisms which don't have the capacity to produce large scale displacement as the DC motor-reel system does.

The exception to the travelling wave behaviour manifests almost exclusively in the small amplitude examples which present less stable profiles and are prone to generation of higher modes due to buckling. When the amount of length compression is large, a single large ruck dominates the length of the base as it is energetically preferable with respect to the elastic bending energy. However a small initial length compression allows for multiple smaller rucks to more easily form.

In the special case of small amplitude ruck and cornflour lubricated surface, the ruck dissipates and reappears at the receiving side, displaying snap-through behaviour (Figure 7a). In this case the surface friction is low enough that the ruck is not stable and collapses when tension is applied across the embedded tendons. The initial compression of the membrane is conserved though, and the ruck reappears at the receiving end of the system where the buckling forces exerted by the tendons are stronger. Larger initial rucks, as well as increased surface friction inhibit this effect.

In future works the travelling wave design will be investigated as a locomoting bioinspired robot or a matter transport application such as a sorting table. Wave membranes offer the possibility for mixed mechano-sensing and actuation as a large resistance applied to the motion of the ruck will result in a change in the tension detected in the tendons.

V. CONCLUSIONS

A method of generating deformation and movement in a soft membrane using only a single actuator and two free tendons is presented. It is demonstrated that a travelling wave can be produced which can transport granular media

and relatively heavy objects, making it highly suitable for applications in matter transport. The size of the initial ruck influences stability, with the smaller ruck size causing the breakdown into higher modes, as well as snap-through behaviour when combined with low friction surfaces. As the membrane travels, its maximum curvature increases and its amplitude decreases. Deformation and warping of the membrane increase with these measures, though tendon winding is not impeded until the tendon becomes straight. The ability to generate travelling waves in a compliant membrane with a single actuator creates opportunities for novel bio-inspired robot locomotion and mixed-media conveyor belts.

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Data Disclosure Statement

All underlying data to support the conclusions are provided within this article.

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