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MECHANICS OF THE WHOLE SKIN LOCOMOTION MECHANISM CONCENTRIC SOLID TUBE MODEL: THE EFFECTS OF GEOMETRY AND FRICTION ON THE EFFICIENCY AND FORCE TRANSMISSION CHARACTERISTICS

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ABSTRACT

In this paper, the effects of cross-sectional geometry and friction on the mechanical advantage and efficiency of the whole skin locomotion (WSL) mechanism concentric solid tube (CST) model are presented. WSL is a novel locomotion mechanism for mobile robots, which is inspired by the motility mechanisms of single celled organisms that use cytoplasmic streaming to generate pseudopods for locomotion. It works by way of an elongated toroid which turns itself inside out in a single continuous motion, effectively generating the overall motion of the cytoplasmic streaming ectoplasmic tube in amoebae. WSL can be considered as a new class of mechanism that converts the expanding and contracting motion of rings to an everting motion of the body.

A brief description of the WSL mechanism is presented first, followed by the mechanics of a single and multiple actuator rings over a CST showing the relationship between the input ring tension force and the output propulsion force for a quasi-static case. Then a study of the force transmission characteristics is presented by studying the effects of cross-section geometry and friction on the efficiency and mechanical advantage of a single actuator ring over a semicircular and composite cross section CST.

INTRODUCTION

Whole Skin Locomotion (WSL) [1] is a biologically inspired alternative fundamental locomotion mechanism for mobile robots inspired by the motility mechanisms of single celled organisms that use cytoplasmic streaming to generate pseudopods for locomotion. The name comes from the fact that the entire outer surface of the robot, which has a body of a shape of an elongated torus, is used as a surface for traction and that the skin is used for the actuation by cycling through contraction and expansion.

The inspiration for this novel locomotion strategy comes from the way certain single celled organisms, such as the *Amoeba proteus* (giant amoeba) or *Chaos chaos*, move. The motion of these organisms is caused by the process of cytoplasmic streaming where the liquid form endoplasm that flows inside the ectoplasmic tube transforms into the gel-like ectoplasm outer skin at the front, and the ectoplasm outer skin at the end transforms back into the liquid form endoplasm at the rear. The net effect of this continuous ectoplasm-endoplasm transformation is the forward motion of the amoeba [1-3].

Directly imitating this cytoplasmic streaming process with a robot is very difficult to do if not possible since it would be very challenging to implement something similar to the endoplasm-ectoplasm transformation in macro scale. Thus, instead of using the process of liquid to gel transformation of cytoplasm, the WSL is implemented by a flexible membrane skin (or a mesh of links) in the shape of a long torus. The skin of this elongated torus can then rotate in a fashion of turning itself inside out in a single continuous motion, effectively generating the overall motion of the cytoplasmic streaming ectoplasmic tube in amoebae (Figure 1).

A robot that uses WSL can move as long as any surface of the robot is in contact with the environment, be it the ground, walls or obstacles on the side, or the ceiling, since the entire skin is used for locomotion. With an elastic membrane or a mesh of links acting as its outer skin, the robot can easily squeeze between obstacles or under a collapsed ceiling, and move forward using all of its contact surfaces for traction, or

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even squeeze itself through holes with diameters smaller than its nominal width as demonstrated in [4].

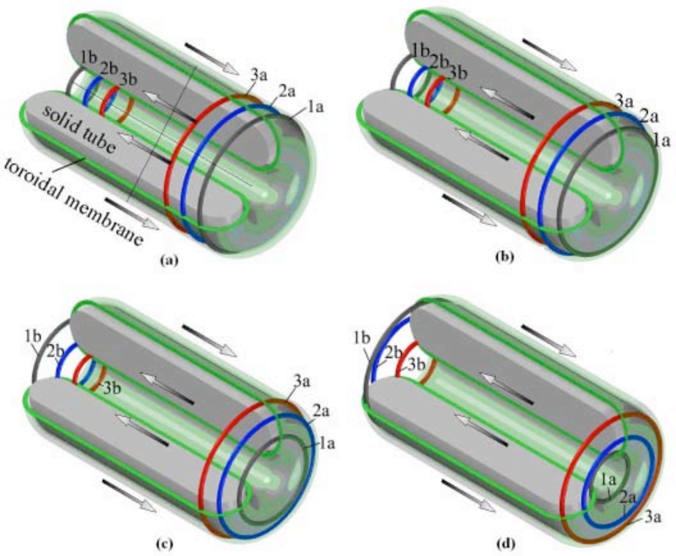


Figure 1. EVERTING MOTION GENERATED BY THE CONTRACTING (1a, 2a, 3a) AND EXPANDING (1b, 2b, 3b) ACTUATOR RINGS FOR THE CONCENTRIC SOLID TUBE WSL MODEL.

Some examples of robots that use the idea of distributed contact locomotion include the rolling stents endoscope [5], and a cylindrical robot with feet distributed over the surface [6,7]. The rolling stent endoscope uses a 'rolling donut' constructed from three stents positioned around the endoscope tip for intestinal locomotion, and the cylindrical robot with distributed feet perform a coordinated shoveling motion of the feet that provides forward propulsion wherever a foot is in contact with any feature in the environment. Another example is a mono-tread robot [8] that uses a steerable single continuous belt. All of these robots share some similar characteristics with WSL in a sense; however their topology and method of actuation are completely different.

In this paper, we present the effects of cross-sectional geometry and friction on the mechanical advantage and efficiency of the WSL mechanism concentric solid tube (CST) model. First, a brief description of the WSL mechanism is presented, followed by the mechanics of a single and multiple actuator rings over a CST showing the relationship between the input ring tension force and the output propulsion force for a quasi-static case. Then a study of the force transmission characteristics is presented by studying the effects of cross-section geometry and friction on the efficiency and mechanical advantage of a single actuator ring over a semicircular and composite cross section CST.

WHOLE SKIN LOCOMOTION MECHANISM

The body of the WSL mechanism is consisted of a toroid shaped skin that either has a solid tube inside (concentric solid tube model, or CST), or is filled with liquid (fluid filled toroid model, or FFT) like that of a common child's toy that is often referred to as a "water worm." The motion of the torus shaped skin is generated by the contraction and expansion of the actuation rings embedded in the skin using several different mechanisms as proposed in [1]. Among these actuation mechanisms, in this paper the analysis of the "rear contractile rings with concentric solid tube" actuation strategy is presented. As the contractile ring near the edge (1a) begins to contract it pulls itself over the rounded edge of the concentric solid tube, pulling the currently inactive rings behind them, as shown in Figure 1(a). When the following contractile ring (2a) approaches the rounded edge it begins to contract, adding to the force of the first ring, as shown in Figure (b). This process continues as the first rings begin to pass completely inside the tube, as shown in Figures 1(c) and 1(d). The active rings will continue to pull the inactive rings allowing for a continuous motion of the membrane skin.

The WSL mechanism is considered as a new class of mechanism that converts contracting and expanding motion of a ring to a toroidal everting motion. Thus, it does not require conventional actuators such as electric motors or linear actuators. To actuate the contracting and expanding rings to generate the desired motion for the WSL mechanism, two different methods were proposed [1], one method for the larger scale implementation, the other for the smaller scale implementation. The larger scale method consists of rings of accordion type hoses that are expanded and contracted using pressurized fluid, such as compressed air. The benefit of this strategy is that a large displacement (strain) can be obtained easily and the actuation force can be made large since it simply depends on the pressure of the fluid in the expanding hoses. These expanding rings can be embedded into the skin of the robot as channels, making it a robust approach of generating the everting motion. The smaller scale method being considered uses rings of electroactive polymer (EAP) strips around the toroid to drive the motion. Active materials maybe the ideal actuators for WSL, since the strain they are able to produce is the type of displacement needed for WSL. Though promising, the general problem of this approach is the lack of force generated by these active materials. Thus, EAPs are only considered for small-scale implementations.

MECHANICS OF THE CONCENTRIC SOLID TUBE MODEL

A simplified analysis of the mechanics for the concentric solid tube (CST) type body with rear contractile rings was performed to gain insight into the mechanics of the simplest WSL mechanism actuation model. In this analysis, the effects of the elastic membrane skin are not considered, which can have a significant effect on the overall mechanics of the WSL CST model.

Nomenclature

η Efficiency of a single actuating ring over a CST

μ The coefficient of Coulomb friction between the contracting ring and the CST surface

ϕ The slope angle of the CST surface in the longitudinal direction

f Distributed force along the inside of a contracting ring in the radial direction (the "squeezing" force of an actuator ring on the CST surface) [force/length]

f_N Distributed normal force on the surface of a CST in the radial direction due to a contracting ring actuator [force/length]

f_R Distributed output "propulsion" force in the longitudinal direction of a single contracting ring actuator [force/length]

f_f Distributed friction force in the longitudinal direction between the contracting ring and the CST surface [force/length]

F The total "propulsion" output force generated by a contracting actuation ring(s) [force]

R The current radius of a contracting ring actuator [length]

s Position of an actuation ring represented as the distance from a fixed reference on the CST, along its travel path on the CST surface in the longitudinal direction [length]

T_R Tension in a contracting ring actuator [force]

n The nominal number of actuating rings per unit length in the longitudinal direction assuming equal distribution

N The number of active contracting actuator rings

Single Contracting Ring Actuator Over a CST

Figure 2 shows the free body diagram of a single contracting ring at the instant when its radius is R and when it is squeezing the membrane over the CST with a distributed force in the radial direction of f (unit: [force]/[length]).

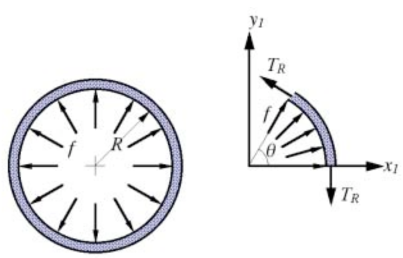
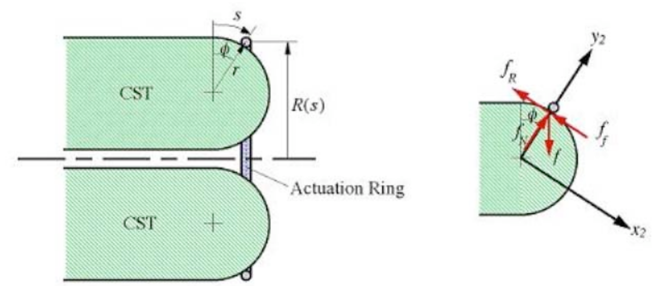


Figure 2. FREE BODY DIAGRAM OF A CONTRACTING RING ACTUATOR

The relationship between the tangential direction tension in the contracting actuator T_R and the distributed "squeezing" force f in the radial direction can be found by

$$\sum F_{x1} = 0 \rightarrow \int_0^{\theta} f \cos\varphi \cdot R \cdot d\varphi - T_R \sin\theta = 0 \rightarrow f = \frac{T_R}{R} \quad (1)$$

where the contracting distributed force f is inversely proportional to the actuating ring radius R, and proportional to the tension (T_R) it can generate. Assuming Coulomb friction between the CST and the inner surface of the actuator ring with a friction coefficient μ, and ignoring the force due to the tension and friction of the elastic membrane segments (which can be significant), the free body diagram for a single contractile actuation ring over a CST is shown in Figure 3 (b).



(a) Cross section of CST with a contracting ring (b) Free body diagram

Figure 3. FREE BODY DIAGRAM OF A MEMBRANE SEGMENT BETWEEN THE CONTRACTILE RING AND CST.

A quasi-static force balance shows the relationship between the tension T_R in the contracting actuator, and the distributed output "propulsion" force f_R in the longitudinal direction (unit: [force]/[length]) a single contracting ring can generate as a function of the slope angle $\phi(s)$ of the CST at the location and the ring radius $R(s)$.

$$\begin{aligned} &\sum F_{y2} = 0 \rightarrow f_N = f\cos\phi(s) \\ &\sum F_{x2} = 0 \rightarrow f_R + f_f = f\sin\phi(s) \rightarrow f_R = f\left(\sin\phi(s) - \mu\cos\phi(s)\right) \\ &\rightarrow f_R = \frac{T_R}{R(s)}\left(\sin\phi(s) - \mu\cos\phi(s)\right) \end{aligned} \quad (2)$$

The radius of the actuating ring $R(s)$ is a function of the position (s) of the actuation ring over the CST and will also depend on the longitudinal cross-section geometry of the CST (shown as semicircular in Figure 3).

The total output "propulsion" force of a single contracting ring over a CST is found by multiplying the longitudinal output force per unit tangential length (f_R) by the circumferential length over which it acts ($2\pi R(s)$). This leads to the following input-output relationship:

$$F(s) = T_R 2\pi\left(\sin\phi(s) - \mu\cos\phi(s)\right) \quad (3)$$

The total output "propulsion" force F of a single contracting ring over a CST is only dependent on the friction coefficient and the slope angle $\phi(s)$ of the CST at the location of the actuating ring, thus the end shape of the CST will have a great effect on the force transmission characteristics and the efficiency of the mechanism, as will be shown in the following sections.

Multiple Contracting Ring Actuators Over a Semi-circular Cross-section CST

The WSL mechanism will have multiple contracting rings as shown in Figure 1. For a system with a discrete number of actuators over a semicircular cross-section CST, the number of active actuators N is

$$N = n\left(r\frac{\pi}{2}\right) \tag{4}$$

for the quarter circular region where the contracting actuators are effective (active region $0 \le \phi \le \pi/2$ in Figure 3), where r is the radius of the semicircular longitudinal cross section (as shown in Figure 3(a)), and n is the number of actuating rings per unit length in the longitudinal direction assuming equal distribution of the actuating rings. The total output force is then the sum of the forces from all of these active actuating rings in this active region as

$$\begin{aligned} &F = 2\pi\sum_{i=1}^{N} T_{R,i}\left(\sin\phi_i - \mu\cos\phi_i\right) \\ &\phi_i = \frac{\pi}{2N}i \rightarrow F = 2\pi\sum_{i=1}^{N} T_{R,i}\left(\sin\left(\frac{\pi}{2N}i\right) - \mu\cos\left(\frac{\pi}{2N}i\right)\right) \\ &\rightarrow F = 2\pi\sum_{i=1}^{N} T_{R,i}\left(\sin\left(\frac{i}{n\cdot r}\right) - \mu\cos\left(\frac{i}{n\cdot r}\right)\right) \end{aligned} \tag{5}$$

The total force output depends on the tension in each of the actuating rings, the friction between the rings and the CST surface, and the ring distribution over the CST.

For future analysis these equations will be generalized by using the CST cross-section geometry represented by its changing radius $R(x)$, as a function of the longitudinal distance along the central axis x, rather than by using the radius as a function of slope angle ϕ as we have shown here for the semicircular cross section geometry.

MECHANICAL ADVANTAGE AND EFFICIENCY

The mechanical advantage and efficiency are used to observe the force transmission characteristics and energy loss of the mechanism over its range of motion. In this section we define mechanical advantage and efficiency for a WSL mechanism with a CST, and present a parametric study of how various parameters such as position, friction coefficient, and CST cross-section geometry affect the total output force and the total output work for a semi-circular cross section CST WSL mechanism.

Mechanical Advantage and Efficiency

The mechanical advantage is used to observe how the total force output of the mechanism changes over the ring actuator's range of motion, for a given ring actuator contracting force. For this system the mechanical advantage is defined as the ratio of the total propulsion output force F over the actuating ring tension input force T_R.

$$M.A. = \frac{F}{T_R} \tag{6}$$

Similarly, the efficiency of the system is defined as the ratio of the output work over the input work by the actuation ring.

$$\eta = \frac{W_{out}}{W_{in}} = \frac{F\cdot\Delta s}{T_R\cdot\Delta c} \tag{7}$$

where Δs is the distance the actuation ring travels on its path, and Δc is the change in the circumference of the actuation ring. The efficiency of the mechanism will show how much work is lost through the friction between the ring actuator and the CST surface.

The Effects of Ring Position and Friction on Mechanical Advantage and Efficiency

In this section we observe how changing the Coulomb friction coefficient between the actuation ring and the CST affects the mechanical advantage and efficiency of the WSL mechanism over its range of motion. Figure 4 shows the efficiency and mechanical advantage of a WSL mechanism with a single actuation ring on a semi-circular cross-section CST body (as shown in Figure 3) plotted against its travel path length with varying friction coefficients (from 0.01 to 1.0).

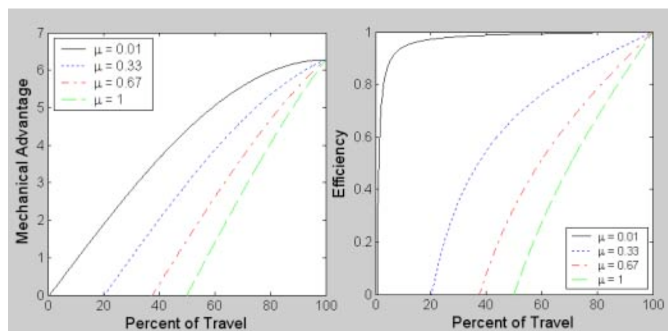


Figure 4. MECHANICAL ADVANTAGE AND EFFICIENCY VERSUS PERCENT OF TRAVEL FOR A CIRCULAR CROSS-SECTION CST WITH VARYING FRICTION COEFFICIENTS.

For the case of a semi-circular cross-section CST, both mechanical advantage and efficiency show similar trends of becoming larger as the contracting ring moves from its initial position (ϕ = 0) with values of zero, to its final position (ϕ = $\pi/2$) where they reach their maximum values. The mechanical advantage is simply a function of the slope angle ϕ and when the CST is flat (ϕ = 0,) perpendicular to the radial direction of the contracting ring, all of the "squeezing" force is used against the normal force f_N, producing no output force. When the contracting ring reaches the tip of the CST, the "squeezing" force of the ring actuator is in the contact tangential direction, thus there is no friction loss and all of the input force is transferred into the total output force, resulting an efficiency of 1. At this position, the mechanical advantage also reaches its maximum value of 2π, which is the ratio between the circumference (tangential direction) and the radius (radial direction) of the circular cross section of the CST. This maximum value is the same for all friction coefficients as there are no contributions from friction at this position.

The friction coefficient has a large effect on both the mechanical advantage and efficiency of the mechanism, as can be seen in Figure 4. The lower the friction coefficient is the faster the efficiency approaches the maximum value, and the sooner it can produce useful work. From these two figures we can observe that a single contracting ring actuator cannot produce any useful work until its reaches a certain critical point (where the curve intersects the x-axis.) This is the point where the propulsion force from the tension in the ring actuator can start to overcome the friction force resulting from the normal component of the squeezing force. The location of this critical point varies from the beginning of the range of motion, for a very small friction coefficient, to half way along the active surface of the cross section, for the maximum coefficient of 1, as this is where the slope angle ϕ equals the inverse tangent of the friction coefficient.

From these observations, the optimal actuation strategy for the many actuation rings (how much tension in each actuation ring in which sequence) can be developed to maximize the output work. Also, in the design phase, insights obtained from this can be applied in deciding the distribution of the actuating rings in the membrane skin to ensure smooth motion of the mechanism.

The Effects of Cross-section Geometry on the Mechanical Advantage and Efficiency

In the previous section a CST with a semicircular cross section was analyzed to see how various parameters affect the efficiency of the mechanism; however, a semicircular cross section is not the only cross-section one can use for the CST. As the efficiency and mechanical advantage depend on the slope angle at the location of the actuation ring, among other parameters, a CST with other geometry cross-sections can be utilized to increase the area of active region and to maximize the overall performance of the mechanism.

Here, as an example, we consider a CST with a composite cross-section geometry consisting of a conical section (the segment of the cross section with a constant slope) with length l_2, connected to two circular sections (with radii r_1 and r_3) with a continuous transition between them, as shown in Figure 5.

Now, we observe how the changing of this cross-section geometry changes the mechanical advantage and efficiency of the WSL mechanism over its range of motion along with the effect of the friction coefficient.

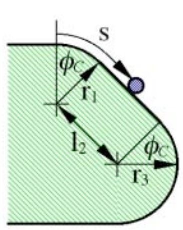


Figure 5. TOP HALF OF THE COMPOSITE CROSS-SECTION CST

Figure 6 shows the mechanical advantage and efficiency of this composite cross-section CST for various friction coefficients. In this model the angle of the area of constant slope is 45° and the parameters for r_1, l_2, and r_3 are all unit length. The plots for efficiency and mechanical advantage show similar trends in the two rounded cross section regions to the plots for the circular cross-section, shown in Figure 4. For the constant sloped cross-section region, the mechanical advantage and the efficiency are constant as shown by the flat sections in the plots of each line. These plots also show that the critical point where the useful work can be produced occurs earlier than with a semicircular cross-section for a given friction coefficient under 1. Thus by introducing the constant sloped cross-section region in the CST cross-section, we can increase the overall efficiency and mechanical advantage and also increase the area of active region (the region where the actuating ring can produce output force).

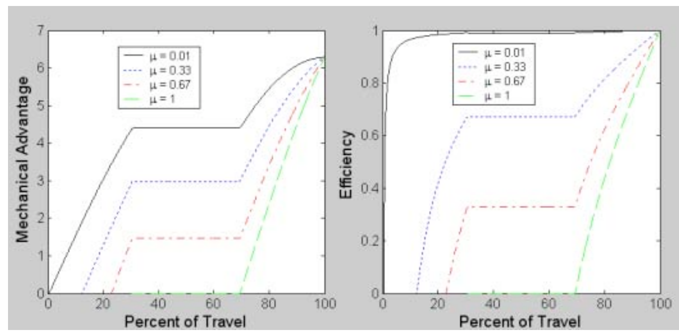


Figure 6. MECHANICAL ADVANTAGE AND EFFICIENCY FOR A COMPOSITE CROSS-SECTION CST WITH VARYING FRICTION COEFFICIENTS.

For this simple composite cross sectional geometry there are four geometric variables, the lengths of r_1, l_2 and r_3, and the angle of the area of constant slope, ϕ_C. For this analysis we want to observe how each of these variables affect the output.

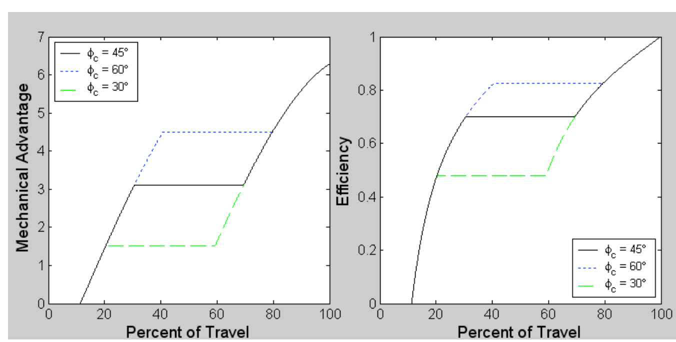


Figure 7. MECHANICAL ADVANTAGE AND EFFICIENCY FOR A COMPOSITE CROSS-SECTION CST WITH VARYING SLOPE ANGLES.

Figure 7 shows the how changing the slope angle changes the shape of the mechanical advantage and efficiency plots. In this model the slope angle is varied from 30° to 60°, while the friction coefficient is kept constant at 0.3 and the parameters for r_1, l_2, and r_3 are all kept constant at unit length. Changing the angle of the area of constant slope of the middle section of the CST moves the constant mechanical advantage and efficiency region up or down. Thus for systems with a high friction coefficient a more effective system could be constructed by increasing the slope of the middle section of the CST which could greatly increase the overall efficiency of the system.

Figure 8 shows how the other geometric parameters (r_1, l_2 and r_3) change the shape of the mechanical advantage and efficiency plots. In this example, the angle of the area of constant slope and the friction coefficient are held at 45° and 0.3 respectively. The actual distance traveled rather than the percent of distance traveled is used in this plot, as changing the lengths changes the end points relative to each other.

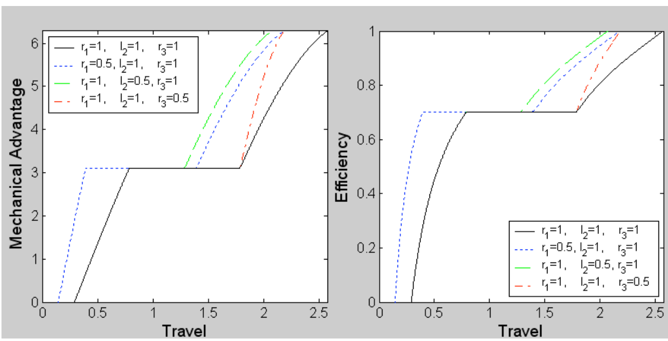


Figure 8. MECHANICAL ADVANTAGE AND EFFICIENCY FOR A COMPOSITE CROSS-SECTION CST WITH VARYING GEOMETRY.

From these plots it can be seen that if the radius of either the first or third section (r_1 or r_3) is shortened the slope of that section of the plot increases, and it will reach a higher mechanical advantage and efficiency sooner. Shortening the length of the second section (l_2) only changes the total distance traveled, and has no effect on the overall efficiency or mechanical advantage. Again, this information will be useful in designing future CST WSL mechanisms to maximize the performance of the system.

CONCLUSION

This paper presents the result of our study of the effects of cross-sectional geometry and friction on the mechanical advantage and efficiency of the whole skin locomotion (WSL) mechanism concentric solid tube (CST) model inspired by the motility mechanism of amoebas. The WSL mechanism works by way of an elongated toroid that turns itself inside out in a single continuous motion, effectively generating the overall motion of the cytoplasmic streaming ectoplasmic tube in amoebae. This locomotion mechanism can turn the entire surface of the robot into the traction surface and the actuator, allowing it to traverse complex terrain that is inaccessible to wheeled, tracked, or legged vehicles.

An analysis of the CST model focusing on mechanical advantage and efficiency was performed. The results show that the cross-section geometry of the CST and the friction between the actuating rings and the CST have a large effect on the mechanics of the WSL mechanism. By changing the shape of the CST cross-section, the plots of the mechanical advantage and efficiency can be "shaped" to increase the overall performance of the WSL mechanism. Insights gained from this analysis can be used for the design of the optimal shape of the CST and for developing actuation strategies for the many actuation rings.

The modeling for this analysis was done using a single contracting ring actuator, and did not take any deformation of the elastic membrane skin into account. This stretching of the membrane will have a significant effect on the mechanics and performance of the WSL system and thus a more detailed model that includes the elastic model of the membrane and pre-tension needs to be developed to more accurately represent the mechanics of the CST-type WSL system.

The work in the immediate future includes an analysis of the CST model taking the membrane skin into account, and a detailed analysis of the FFT model. Working prototypes are currently being fabricated using different techniques, skin materials, and actuators.

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