Shear Strengthened Granular Jamming Feet for Improved Performance over Natural Terrain

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***Abstract*— Walking on natural terrain like soil and rock is a challenging problem that has been approached from a variety of strategies such as using sophisticated control methods, compliant legs, and compliant feet. In this paper we explore how to modify granular jamming feet for walking applications by adding stabilizing internal structures. Previous work has explored how granular jamming technology can be used to create compliant and stiffness changing feet that enable locomotion over a diverse range of natural terrain by allowing robot feet to conform around 3D multicomponent terrain such as wood chips and gravel and stiffen, preventing slip. To date, no work has been done to tune granular jamming feet for the specific application of walking. We show that adding internal structures to granular jamming membranes can increase the force they are able to resist without slipping by 1.5x while maintaining their ability to conform around obstacles. When attached to a robot, we see increases in speed of up to 1.4x, decreases in the duty cycle necessary to reach desired foot trajectories of up to 5%, and increases in traction force of up to 1.2x over a diverse set of natural terrain.**

***Index Terms*— Soft robot materials and design, legged robots, soft robot applications, granular jamming**

I. INTRODUCTION

The two main design approaches for mobility over natural terrain are wheels and legs. Historically, wheeled robots have been used for applications such as exploring the surface of mars or navigation through disaster zones, but often wheeled vehicles perform poorly when confronted with features such as obstacles, gaps, or soft and deformable terrain such as sand or mud [1]. In contrast, legged robots have more success at stepping on or over obstacles [1], but often fail when they are unable to create a stable foothold. Failure includes characteristics such as sinking into terrain instead of making forward progress and slipping when attempting to push off during a stride. It is advantageous to have robots that are able to walk effectively over natural terrain, since these are the situations where we would most like robots to take the place of humans due to safety (eg. disaster and conflict zones) or accessibility concerns (eg. extraterrestrial exploration).

Robot feet are usually made from stiff material and are not capable of varying shape or stiffness while walking. However, when transitioning between terrain types it would be advantageous to have robot feet that can actively change shape or stiffness to optimize ground contact forces and traction. For example, on sand it may be advantageous to have a flat foot with a large surface area to prevent sinking, but over a pockmarked lunar surface it may be advantageous for part of the foot to sink into a crevice and grip onto it.

Granular jamming appendages offer a solution in which secure, rigid footholds can be made yet feet can be soft when first stepping down to adapt and conform to the surface profile. Granular jamming technology can enable reconfigurable feet – we hypothesize that they can allow a foot to spread out and conform around obstacles as it touches down, and then stiffen, providing a platform to push off from. But adapting granular jamming for use in feet has its own obstacles, such as an inability to withstand large shear forces without failing [2], especially at the interface of the granular matter and the collar at the base of the foot (Fig. 4b).

Previous work has shown that adding reinforcing structures can increase the peak shear force that a dry granular media is able to withstand [3]. In this paper we aim to adapt granular jamming for use as a robot foot by adding internal structures to allow the feet to better resist shear forces. We then attach these feet to a commercially available hexapod and characterize it's performance over natural terrain.

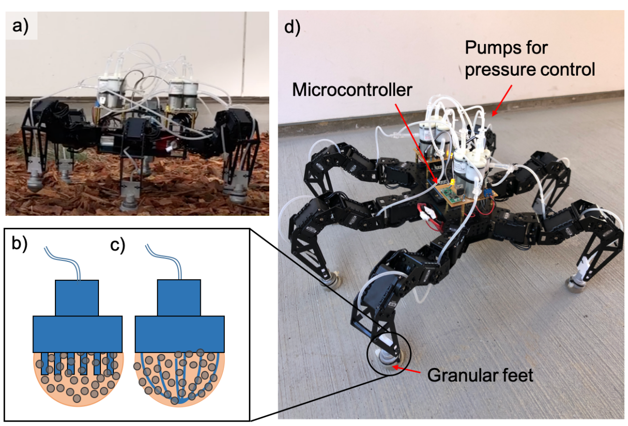

Fig. 1. Hexapod with granular jamming feet. a) Untethered hexapod with attached feet and on-board fluidic control on wood chips. b) Foot design composed of elastic membrane filled with granular media and reinforced with rigid rods. c) Foot design composed of elastic membrane filled with granular media and reinforced with abrasive fibers. d) Schematic of hexapod.

The jamming of granular particles has been used to explain how mechanical stability arises from disordered particulate systems as the packing fraction increases [4], [5]. Researchers have used this stiffness changing property of granular materials to design variable stiffness actuators

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by enclosing particles in a membrane at a packing fraction near the jamming transition. The particle filled membrane is soft and can conform around obstacles in its normal state but when the packing fraction is increased slightly via vacuum, the particles jam, and the actuator becomes rigid. Granular jamming actuators have been used for a variety of robotic applications including grippers with simple control and actuation systems [6], [7], jamming skin enabled locomotion [8], variable stiffness haptic devices [9], [10], and stiffness changing manipulators for minimally invasive surgery [11].

To date, several robot designs with simple actuation strategies have been explored for navigating unstructured terrain including rigid, c-shaped legs [12], kirigami skins [13], jamming skin enabled locomotion [8], and 3D printed soft actuators [14], but all these designs still do not feature feet that are able to conform around obstacles. Researchers have also explored using simple rigid feet with sophisticated control strategies [15], [16] to enable effective locomotion. While this has allowed robots to walk over a wider range of terrain, walking speed is very slow as each step is computationally expensive.

Previous work has begun exploring how granular jamming actuators can be used as robot feet [2], [17] but so far researchers have only demonstrated locomotion on flat surfaces and single, small obstacles placed on flat surfaces, not on natural or irregularly shaped terrain. We aim to address some of the challenges of using granular jamming actuators as robot feet and expand upon the range of surfaces that these feet are able to walk over. One of the main challenges for in doing this is that a foot has to support shear as well as normal forces, whereas in a task such as gripping, previous work has often explored only normal pull-off forces [6]. In granular jamming, unstable, fragile jammed states are common in shear [18], which puts granular jamming actuators at a disadvantage for use in walking.

We propose to address this challenge by adding internal structures inside the granular jamming casing to increase the force the foot can withstand in shear. The inspiration for the design of these structures is drawn from natural and engineered slope stabilization techniques to reduce landslides and lessen erosion. These methods include using plant roots to naturally stabilize a slope [19] or adding rigid support elements such as piles [20]. We then attach this modified granular jamming foot to a robot and quantify the performance benefits of both passive and active jamming over various types of natural terrain.

II. DESIGN AND FABRICATION

Our foot consisted of a reversible granular jamming sack composed of a nonporous elastic membrane (latex) filled with a granular media (coffee grounds). The elastic membrane was attached at its widest point to a stiff ankle printed from PLA (Fig. 1b,c), resulting in a foot in the shape of a half sphere (diameter 2.6cm). In its normal state the sack was deformable but negative pressure was applied, the particles jammed together and turned solid. Positive pressure was then used to reset the sack to its unjammed state. For the characterization tests, we controlled the internal pressure of the sack using a fluidic control board [21] capable of generating 10 psi of negative pressure.

We then added one of two classes of internal structures that protruded into the membrane from the base (Fig. 1 b,c). The structures were inspired by structural engineering techniques such as pilings and fiber-reinforced soil or concrete, commonly used for increasing structural integrity and resisting shear loads. The first class of internal structures consisted of 3D printed PLA rods of radius 1 mm or 2 mm and length 6 mm in both cases. The base and rods were printed as one piece out of PLA. For the 1mm radius rods, the spacing of the rods consisted of two rings of 12 rods each, spaced 7 mm and 10 mm from the center. For the 2 mm radius rods, the spacing consisted of one ring of 12 rods, spaced 7.5 mm from the center. The second class consisted of abrasive fiber cords of diameter .46 mm, .76 mm and 1.4 mm coated with aluminum oxide grit (Mitchell Abrasives). The cords were mounted into blind holes printed into the PLA base, and sit entirely within the granular media, not contacting the latex membrane. We then characterized the performance of these structures.

III. CHARACTERIZATION

A. Ability to Resist Shear Forces

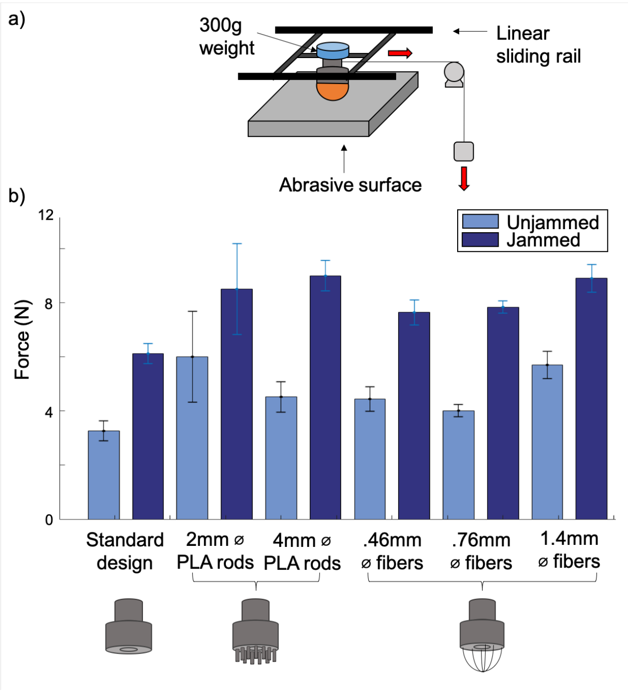

Fig. 2. Shear force tests. a) Shear setup. b) Passively and actively jammed shear strength before slipping on a pebbled surface.

We characterized the shear force that each foot is able to resist without slipping in both the passively jammed (no vacuum but jammed due to the vertical weight) and actively jammed cases. To do this, the foot is placed in contact with a representative natural surface composed of rough pebbles secured to a surface (average diameter=.5 cm) and vertically loaded with a 300g weight (roughly 1/6 of our hexapod weight). The foot is attached to a rail that constrains it to travel horizontally while allowing it to move freely vertically (Fig. 2a). We use a pulley system to apply increasing tangential force and measure the force at which the foot begins to slip.

In the passively jammed case (Fig. 2b), all designs with internal structures increased the shear strength before slipping compared to the standard design, with the small diameter stiff rods and the large diameter abrasive fibers performing the best. For these two cases, the diameter of the internal structures were similar (1 mm and 1.4 mm for the rods and fibers respectively).

When jammed, both the internal PLA rods and the abrasive fibers increased the shear strength before slipping, compared to the standard design (Fig. 2b). As the diameter of the internal structures increased, the shear strength increased (for each type of internal structure).

B. *Ability to Conform Around Obstacles*

Although adding internal structures can increase the strength of our feet, the structures also have the potential to decrease the foot's ability to conform around obstacles in its unjammed state compared to a foot without internal structures. This is due to the fact that the internal structures do not experience a stiffness change when transitioning from jammed to unjammed, and maintain their original stiffness throughout a cycle. This results in an increased composite stiffness of the foot while unjammed due to the contribution of the stiff internal structures.

We used Frustrated Total Internal Reflection (FTIR) to measure the area of contact between two surfaces - the granular foot and the ground adjacent to an obstacle the foot was placed partially over. We built an FTIR sensor composed of white LEDs illuminating the edge of a rectangular polycarbonate plate. We then built a platform over the sensor that allows the foot to be displaced vertically around an obstacle on the plate (Fig. 3a). Images were captured with minimal ambient light and a reference frame was used to subtract out ambient light in post processing. By measuring contact area, we aim to measure which internal structures do not decrease the ability of the foot to conform around obstacles.

A 500g weight was applied at the ankle of the foot for a constant normal loading of the foot onto the plate and step.When the foot made contact with the plate, it illuminated the contact area. Using a camera, we measured the contact area that a passive soft foot could achieve around an obstacle - a rigid acrylic step half the height of the foot. All tests were done in the passively jammed state with 5 trials for each design.

As seen in Fig. 3b, the rigid PLA rods limit the ability of the foot to conform around a step to about 50% of the performance of a foot with no internal structures. The thin fiber design was able to achieve a similar contact area to the standard design, the mid-thickness fibers performed about 2.5x as well as base design, and the thickest diameter of fibers performed about 75% as well as the standard design. We hypothesize that the thickest fibers may behave similarly to the rigid PLA rods in that they limit the softness of the foot. We hypothesize that the mid-thickness fibers performed well due to the fact that the fibers are flexible enough to conform around obstacles but also stiff enough to push against the membrane to reset the foot back to its original shape between trials, resetting the compaction of the granular media inside the foot.

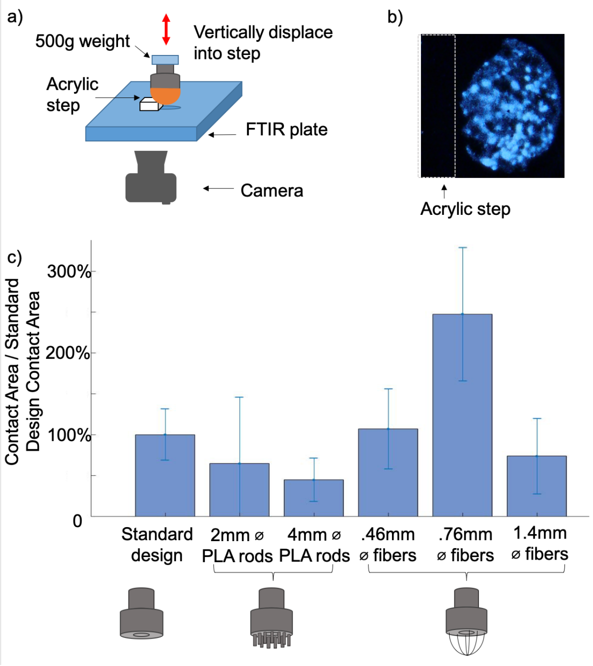

Fig. 3. Area of contact tests. a) Total internal reflection setup for area of contact tests. b) Sample camera image of FTIR plate illuminating contact area of the foot with the acrylic step outlined with a white dashed line.c) Results for area of contact tests, y axis is total contact normalized against contact area for standard design.

As a result of the previous two tests, we decided to implement the mid thickness abrasive fiber design onto a robot since it performed well in shear as well as increased the ability of the foot to create ground contact around obstacles.

IV. VALIDATION ON HEXAPOD

We then validated this new foot design on a commercially available hexapod (Arcbotix, Fig. 1d). We attach either 1) the stock feet composed of a 5mm thick laser cut acrylic plate (width ≈1 cm) with a rubber pad encasing the acrylic of thickness 1.5mm, 2) the base granular design without any reinforcing structures, or3) a fiber reinforced granular jamming foot (Fig. 4a,b,c respectively). We designed and fabricated an on-board pneumatic system similar in function to the fluidic control board presented in [21]. The system is capable of generating negative pressure (-10 psi) to control the jamming of the feet, and positive pressure (1 psi) to unjam the foot between each step by adding connections to the intake and outlet of a pump, respectively.

For the active foot tests, we jammed the foot in sequence with the gait (Fig. 5). We chose an alternating

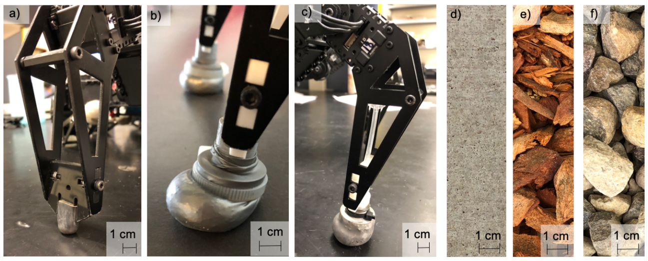

Fig. 4. Foot designs and terrains tested. a) Rigid foot. b) Granular jamming foot, base design, displaying failure in shear.c) Granular jamming foot with fiber reinforcement. d) Concrete (flat ground). e) Wood chips. f) Loose Rock.

tripod gait since it is a common, stable gait used by many hexapods.Each foot is jammed immediately after it comes in contact with the ground and the foot has time to conform around its environment (t = 0 s in the gait cycle). The jamming action takes approximately 0.5 s to rigidify. Once the stance phase is completed the foot is then unjammed with positive pressure and the foot lifts. The time it takes the foot to fully jam once negative pressure is applied (≈ 0.5 s) is negligible compared to the time for one step cycle (3 s).

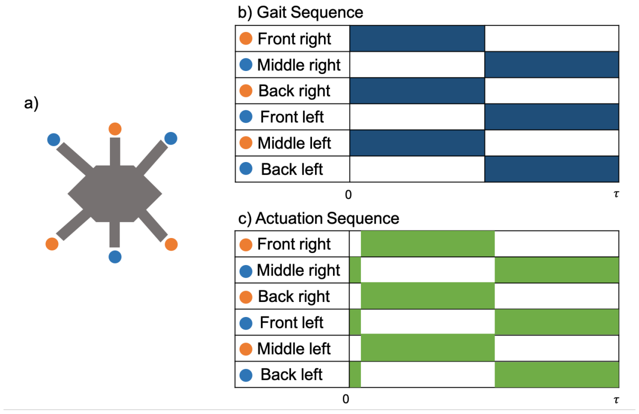

Fig. 5. Gait Sequence. a) Hexapod top view. Motion is from left to right. b,c) Actuation and gait sequences for one cycle of the hexapod gait. The shaded region corresponds to when the foot is in contact with the ground. The shaded region in the actuation sequence corresponds to when negative pressure is drawn. The non-shaded region in the actuation sequence corresponds to positive pressure.

A. Speed Benefit

Jamming of granular feet can occur from passive effects such as weight being applied to the foot, and active control of the internal pressure. In order to quantify the effect of both passive and active jamming, we measured walking speed with a tripod gait over flat ground, wood chips, and loosely packed rock of diameter approximately 2/3 the size of the foot (N = 5 for all trials). For all trials, the hexapod carried the on board pumps and custom controller.

The first qualitative observation that we noticed between the feet with no reinforcing structures and the fiber reinforced feet was that the fiber reinforcement reduced failure in shear at the interface of a foot's bottom surface (ankle) and the jammed granular substrate. An image of the base granular foot failing in shear is seen in Fig. 4b. This type of failure was not seen in the tests conducted with the fiber reinforced foot (Fig. 4c).

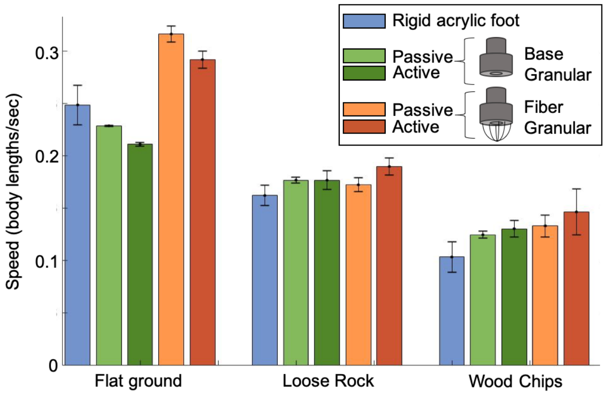

Fig. 6. Speed of each type of foot in body lengths per second over flat ground (concrete), loose rock, and wood chips.

As seen in Fig. 6, on flat ground we see a statistically significant speed improvement between the rigid and base granular feet compared to the fiber granular feet, in both the passive and active cases (one-way ANOVA, F = 99.3), with the largest speed increase seen using the passive fiber reinforced feet. Over loose rock and wood chips, we see a statistically significant increase in speed from a rigid foot to the active base granular foot, and both the passive and active fiber reinforced foot (one-way ANOVA, F = 9.81, 7.48 respectively). We also see moderate increases in speed between the base granular design and the actively jammed fiber reinforced design.

We see that over both flat ground and loose terrain such as rocks or wood chips, granular feet enable benefits in walking speed, with the choice of passive versus active jamming determined by terrain type. We see that over smooth, flat ground passive jamming fiber reinforced feet perform the best, likely due to the ability to create a large and stable surface area of contact, as well as reduce energy loss at collision. Over loose rock (average diameter = 1cm) and wood chips, fiber reinforced active jamming feet perform best, likely because these feet are able to fill gaps in the substrate in their soft state and then jam, creating a stable foothold and reducing slip at the interface between the robot and the substrate. We also see qualitative increases in the longevity the fiber reinforced design as compared to the base design, due to a reduction in shear failure (as seen in Fig. 4b).

B. Duty Cycle Necessary to Reach Desired Foot Trajectory

We next looked at how granular jamming feet can reduce the time it takes for the robot to reach its desired foot trajectory during a step. We measure the duty cycle of the motors during the gait to determine how much time the servos took to correct themselves and reach each desired foot trajectory during a step on both flat and irregular terrain. We define the duty cycle to be time to reach control stability over stance duration. Control stability is defined as servo position register error below 10.

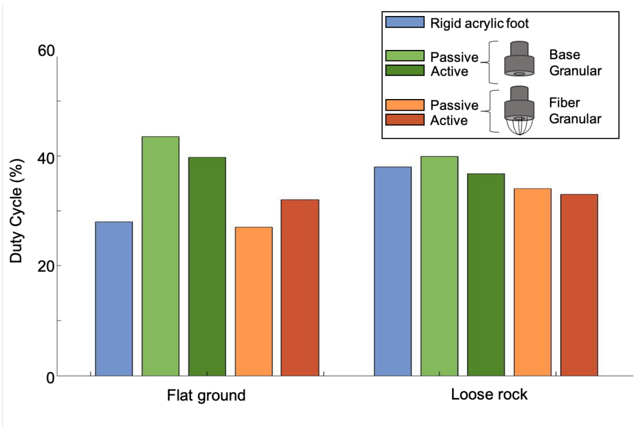

Fig. 7. Motor duty cycle to reach desired foot trajectories over flat ground and loose rock.

In all cases, we see that the fiber reinforced granular feet are able to reach stability faster than the base granular design. On flat ground, active fiber reinforced granular feet take slightly longer to stabilize than passive fiber reinforced granular feet and rigid feet (avg duty cycle over >50 steps of 32% vs 27% and 28% respectively), but still perform better than the base granular design (45.5% and 40% for passive and active respectively) (Fig. 7). On loose rock, both passive and active feet help the robot reach its desired foot trajectories faster than rigid feet or the passive or active base granular feet (34% and 33% vs 38%, 40%, 36.8% respectively).

We see that adding compliance to the foot provides an advantage over loose terrain, but active jamming only provides a slight advantage compared to passive jamming. We also find that adding compliance does not hurt robot performance on flat ground, since leaving the foot in the passive conformation results in similar stabilization duty cycles to rigid feet. This suggests that granular jamming feet should be used in all terrain types in order to minimize duty cycle, with the choice of passive versus active jamming determined on a terrain by terrain basis. We also found it interesting that active jamming takes the same duty cycle on flat and loose terrain, which could have potential to simplify robot control in the future.

C. *Maximum Net Thrust*

The final performance metric we explored was the maximum net thrust that the robot with attached feet was able to produce over various natural terrains. Drawbar pull tests are often used to determine an exploration vehicle's maximum net thrust over loose terrain [22] and can allow us to quantify the performance limits of our feet.

We measured maximum traction force by attaching a linear elastic element (TheraBand) to the back of the robot and fixing the other end, then allowing the robot to walk forward until it reached the limits of its load pulling ability (Fig. 8a. We then measured the change in length of the linear elastic element from fully extended with no stretch to fully extended with stretch (dx) caused by the robot to compute the maximum traction force that the robot could generate.

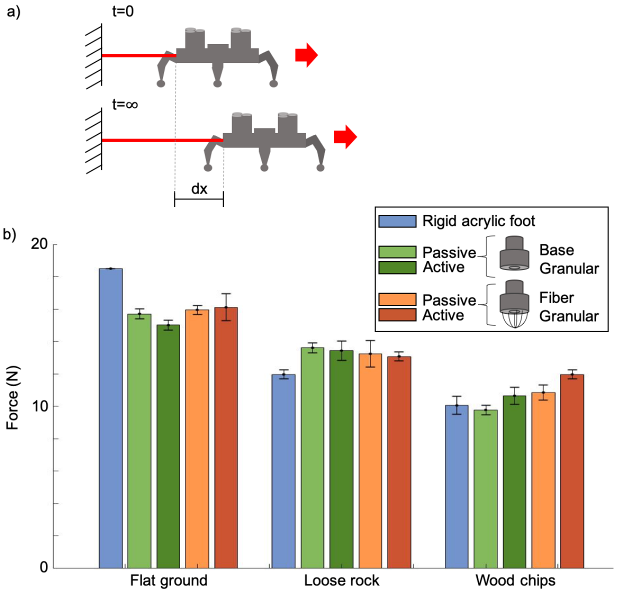

Fig. 8. Drawbar pull test. a) Experimental setup with hexapod attached to a linearly elastic element, measuring change in length to determine force. b) Drawbar pull test results to measure maximum thrust over loose terrain.

As seen in Fig. 8b, rigid feet were able to generate more traction force on flat ground than any type of granular feet (statistically significant with one-way ANOVA, F = 27.81). Over loose rock, all granular feet were able to generate more traction force than rigid feet (statistically significant with one-way ANOVA, F=4.86), but all granular feet performed similarly to each other, regardless of internal structure or jamming. We hypothesize that this limit is set by the force at which the rocks slip internally among each other, causing loss of traction not related to the foot internally or the foot-rock interface. On wood chips, active fiber reinforced granular feet were able to generate more traction force than any other type of foot (statistically significant one-way ANOVA F = 11.14).

In summary, over rigid terrain a rigid foot is able to generate more force compared to the granular jamming feet, which slip internally in their unjammed state, causing the robot to slip backwards when at its limits.Over loose terrain, granular jamming feet will increase a robot's traction, and therefore max net thrust, compared to rigid feet, due to the ability to create a larger area of contact with the uneven terrain, as seen in the results of the area of contact tests (Fig. 3). And in some cases, such as loose rock, the limit is determined by the substrate slipping on itself.

V. CONCLUSIONS

In this paper we have presented a new class of granular jamming feet for legged robot mobility. Our feet incorporate new internal structures that enable a hexapod robot to walk over varied terrain with lower control effort and larger traction force. The increases in robot performance are likely due to the ability of jamming feet to conform around obstacles and then to become rigid, enabling a stable and high shear resistant foothold. We see that a granular jamming soft foot with abrasive fibers can still conform around obstacles, which is desirable, but can also increase it strength in shear, an important metric for walking. The results presented here highlight the performance benefits a robot can see with these new foot designs. The first two tests show the result for a single foot, and are generalizable to other legged agents. The tests on the hexapod test bench demonstrate trends that we believe would be similar in other legged robots.

We found it surprising that even a passively jammed foot imparts benefits in many situations, without need for actuation or control. In the case of flat ground, passive granular feet give the best results likely due to the ability to create a large and stable surface area of contact, as well as reduce energy loss at collision. In cases where the ground is likely to shift underfoot (e.g. loose rock), it is advantageous to have a passive foot that remains soft for the whole gait cycle so that the foot can re-adapt to the terrain underfoot as the terrain shifts within a step. In cases where the ground is rough but does not shift (e.g. wood chips), it is advantageous to have a foot that lands in a soft state, conforms around the terrain, and then stiffens, grabbing on to the terrain and using it as a platform from which to push off.

This finding enables future work that can focus on minimizing control and actuation effort by selectively jamming the feet or leaving them passive based on the terrain. Passively jammed feet could greatly reduce the energetic costs of walking compared to the actively jammed feet, which require a running pump. Incorporation of soft sensors on the bottom of the feet would enable sensing of ground stiffness as the robot transitions between terrain types, which can allow active selection of foot stiffness to best suit the terrain. Improvements in low-cost legged robotic mobility can help robots gain access to currently inaccessible terrains and environments. Strategies that utilize active modification of the shape and mechanical properties of appendages are a promising route to improved mobility in open-loop, sensor deprived environments. Future improvements of granular jamming foot design coupled with specific control and activation strategies provide an exciting new direction for legged robot mobility.

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