ORIGINAL ARTICLE

Prosthetic Jamming Terminal Device: A Case Study of Untethered Soft Robotics

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Abstract

This article illuminates the major and often overlooked challenge of untethering soft robotic systems through the context of recent work, in which soft robotic gripper technology enabled by jamming of granular media was applied to a prosthetic jamming terminal device (PJTD). The PJTD's technical and market feasibility was evaluated in a pilot study with two upper-limb amputees. A PJTD prototype was tested against a commercial device (Motion Control electric terminal service with a one degree-of-freedom pinching mechanism) using two existing hand function tests: the first quantified the device's speed in picking and placing small blocks and the second evaluated a person's ability to perform activities of daily living (ADLs). The PJTD prototype performed slightly slower than its commercial counterpart in the first test. While both participants successfully completed all the ADLs with both devices in the second test, the commercial device scored marginally higher. Results suggested that PJTD can have potential benefits over existing terminal devices, such as providing the capability to firmly grasp tools due to the ability of PJTD to conform to arbitrary surfaces and reducing compensatory shoulder movements due to its axisymmetric design. Some downsides were that users reported fatigue while operating the PJTD, as most operations require pushing the PJTD against target objects to adequately conform to them. The greatest drawback for the PJTD is also a major roadblock preventing a number of soft robotic research projects from making an impact in real-world applications: pneumatic technology required for operating the PJTD is currently too large and heavy to enable compact untethered operation.

Keywords: prosthetic, hand, upper-limb, amputee, myoelectric, soft, gripper

Introduction

SOFT ROBOTICS HAS BEEN a growing research field in recent years.^{1–3} However, one major obstacle preventing many research-level prototypes from becoming real-world solutions is the lack of actuation and power components that are small and lightweight enough for systems to operate untethered. This is a practical issue, for example, for research focused on developing pneumatically actuated mobile robots whose bodies can exhibit enough compliance to navigate tight spaces that traditional robots are not able to,^{4–6} where the components (pumps, valves) required to operate these systems are still bulky and unyielding.

We experienced this challenge firsthand when we developed a prosthetic jamming gripper prototype and tested it

with upper-limb amputees (ULAs). Empire Robotics—the company commercializing jamming grippers for industrial applications—in conjunction with Liberating Technologies, Inc., a leading manufacturer of upper-limb prosthetic components, developed the Prosthetic Jamming Terminal Device (PJTD), a functional terminal device composed of granular media contained in an air-impermeable membrane. This technology leverages the unique jamming behavior of granular materials to create a robotic gripper that can transition between compliant and rigid-like states, enabling it to passively conform to objects, after which it vacuum hardens to rigidly grasp objects.^{7,8} In the pilot study presented here, the system for ULAs was designed such that a jamming gripper was located in the same location that the user's prosthetic hand would be in and myoelectric signals from the user's

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forearm would control the operation of the device (to either harden or soften the gripper to grasp or release items, respectively). The focus of the work being presented was not to develop fundamental enabling pneumatic technology (such as pumps); rather, it was to apply soft robotic research to the real-world application of prosthetic devices, where the integration of all the components is crucial to utility and usability of the product.

Potential benefits of the PJTD over common functional prostheses (such as the Otto Bock Greifer and the Motion Control powered electric terminal device [ETD]) include that it enables custom surface contacts rather than rigid “pinching” contacts between the gripper and target objects, thereby providing improved gripping capabilities with lower applied local forces, and the PJTD can be considerably less sensitive to gripper orientation because of its single-bodied symmetry and therefore eliminate awkward compensatory movements of the user’s shoulder and elbow when aligning the device with an object.

With these potential improvements over existing functional terminal devices, the PJTD was conceived to benefit users in performing activities of daily living (ADLs) at home and the workplace. There are many ULAs living in the United States,^{9,10} with 50k new upper-limb amputations performed each year.¹¹ The documented percentage of ULAs who use a prosthesis has ranged from only 27%¹² to 56%¹³; these small numbers are likely due to the limited capabilities of existing prosthetic terminal devices and indicate the potential for improvement in existing technologies. People with upper-limb absence (especially from work-related trauma) also often lose their functionality in their current jobs and must consider alternative occupations or even retirement due to pain or disability.^{14–16} Therefore, effective functional terminal devices could greatly improve the livelihood of many individuals.

In this pilot study, the PJTD was compared against functional prostheses (Greifer and ETD), as opposed to multi-articulated prosthetic hands (such as the Steeper Bebionic, which mimics the appearance of a human hand and is preferred for cosmetic reasons in, for example, social scenarios), because functional prostheses are often preferred by users in home and work environments that require the devices to be more durable and robust. Novel articulated prosthetic hands have been explored in research,^{17,18} but few have been commercialized due to the practical limitations of using more complex solutions over more simple and commercially available ones.

Materials and Methods

The work detailed in this article was performed as a Phase I SBIR effort funded by the NIH. The goal was to develop a PJTD prototype and test it in a pilot study with ULAs to evaluate its functional and market feasibility. The process for achieving this was as follows: (1) coordinate with an independent occupational therapy consultant to select hand function tests for evaluating PJTD; (2) develop a PJTD prototype and test it with able-bodied users; and (3) use the knowledge gained from (2) to refine the gripper design and test methods to develop a ULA-compatible PJTD prototype and test it against existing terminal devices with ULA subjects.

This study was approved by NEIRB, and all human subjects were consented with an approved form and certified staff.

Hand function tests and PJTD requirements

Our team worked with an independent consultant from Single-Handed Solutions who specializes in educating clinicians and people with upper-limb challenges, including amputees who use prosthetic technologies, to select candidate hand function tests. Various methods were considered (including the Southampton Hand Assessment Procedure, the Unilateral Below Elbow Test, the Activities Measure for Upper Limb Amputees), most of which were designed for the human hand. Our goal was to identify a set of tests that could (1) evaluate the utility of PJTD in enabling a user to perform ADLs and (2) quantify the performance of PJTD in an objective manner (as opposed to many functional outcome measures that rely on subjective user self-report measures). Two outcome measures were selected:

- (1) Modified box and blocks (MBB): Box and Blocks is a test in which a user utilizes one hand to transfer blocks from one side of a box to another, with a partition separating the two sides. The performance metric of interest is speed and can be quantified objectively. The original test specifies that the test starts with many blocks randomly oriented on one side of the wall, where the random spacing between blocks could have a significant effect on how well gripping technologies could interface with the blocks (Fig. 1a). To minimize the number of variables in the test, a more ordered system of blocks was utilized (Fig. 1b), as outlined in the MBB test protocol¹⁹ that has been used previously to test various prosthetic interventions; this version of the test starts with 16 blocks placed evenly apart on one side of the box.
- (2) UNB (University of New Brunswick) Test of Prosthetics Function: The UNB test encompasses a series of tests for evaluating the functionality of prosthetic devices for various age groups, from young children to young adults, where each subset of tests is composed of ADLs. These tests were selected because they evaluate the ability for individuals to function while using a prosthesis, without specifying how a prosthesis must be used to complete a task. The tests for ages 13–21 were selected because it is the oldest age group represented in the test protocol. For this age group, there are three functionally equivalent subtests, each consisting of 10 tasks (such as carry a tray of items, chop an apple, and open an umbrella). Able-bodied test subjects attempted Subtests 1 and 3; this was downselected to Subtest 1 only for amputee subjects to minimize fatigue experienced by participants. Single Handed Solutions scored the UNB tests to ensure consistent scoring. The UNB test score has two main components: spontaneity of use of the device (i.e., the subject’s approach to completing a task using the technology) and skill of use (i.e., assessment of the execution of the task itself).

Figure 1c–f present photos from a preliminary test session conducted with an able-bodied user performing UNB tasks with both the PJTD and the Motion Control ETD. The subject used the two prostheses differently in certain tasks when optimizing for the ease of performing a task. For example, the subject used the PJTD to hold the hammer when putting a nail

FIG. 1. Photos of an able-bodied person using various terminal devices in a preliminary trial: (a) with a PJTD prototype in a Box and Blocks test; (b) with an ETD in an MBB test; (c) with the Greifer in an MBB test; (d) with a PJTD prototype in a University of New Brunswick task where the user was asked to cut a hard food using a knife and fork (here, PJTD was used to hold the knife for cutting); (e) with an ETD completing the same task as in, but using the terminal device to hold the fork for stabilizing the food; and (f) with a PJTD prototype gripping the handle of a cleaning tool, where the user used their contralateral hand to shape PJTD around the handle. ETD, electric terminal device; MBB, modified box and block; PJTD, prosthetic jamming terminal device. Color images available online at www.liebertpub.com/soro

into a piece of wood, but used the ETD to stabilize the nail to complete the same task. An additional observation was that a person can use their opposing nonprosthetic hand to help conform the PJTD around a target object to increase the device's gripping capability (Fig. 1f).

Able-bodied tests

The purpose of conducting tests with able-bodied subjects was to refine the PJTD system and protocol for testing with amputees. Using Empire Robotics' extensive experience in developing jamming gripper technology, a prototype was designed and built that could be operated by an able-bodied user in place of their dominant hand.

Three able-bodied users participated in the studies, but only two completed the tests with all three terminal devices (Fig. 1): (1) the Otto Bock Greifer, a one-degree-of-freedom (DOF), two-fingered device with flat, parallel pinching surfaces; (2) the Motion Control ETD, a one-DOF device with two metal hooks that pinch together as "fingers"; and (3) a PJTD prototype that was operated using a small vacuum pump (within a $7.5 \times 7.2 \times 2.9$ cm envelope and with an 11 LPM maximum flow rate). A PJTD system operated using an off-board compressed air supply with a Venturi vacuum generator with maximum flow rate of 90.6 LPM was also tested, as it was hypothesized that a possible use-case for the PJTD is when compressed air is reasonable to use, for example, in a factory assembly line. However, after consulting with a prosthetist, it was determined that this is a rare use case and a feasible product cannot be tethered.

The design of the systems used by able-bodied subjects is similar to those shown in Figure 1. During each session, terminal devices were attached to the user's dominant arm using an N-abler (Texas Assistive Devices), which prevented wrist flexion and extension to mimic an amputee's use of the

devices. Sugar tong splints were used to prevent pronation/supination of the wrist/forearm. In the beginning of each session, users were taught how to use each of the devices (each could be controlled using a momentary switch located beneath the user's thumb on the hand being tested) and were encouraged to experiment with the devices to become familiar with them. During testing, the order of terminal devices used was randomized for each user.

Results for the MBB test indicated that the PJTD produced similar results as the ETD, but both the ETD and PJTD took $\sim 20\%$ longer to complete the test than the Greifer.

Design of amputee-compatible PJTD

Compared to the able-bodied system, LEDs were included to indicate the user's intent to grip an object (harden the gripper) or release an object (soften the gripper) through myoelectric sensors on the user's forearm; this would help ease UNB test scoring. In addition, able-bodied testing revealed that indicating the vacuum level in the device would provide feedback to the user to improve efficiency when gripping objects; therefore, a pressure gauge was added to the final system to indicate when adequate vacuum levels were achieved (Fig. 3).

Figure 2 presents a diagram of the electrical and power components of the system, in which users provided their own commercial prosthetic socket with myoelectric sensors that output electrical signals generated by the user's forearm muscles. An Otto Bock quick-disconnect (QD) wrist attachment was used to both electrically and mechanically connect the prosthesis to the terminal devices.

As in typical upper-limb myoelectric prostheses, two myoelectric signals can be controlled from the user's forearm muscles. These two myoelectric inputs were mapped to pull vacuum (grip an object) or inflate the gripper with positive

FIG. 2. A diagram of the electrical and power components in the PJTD system.

pressure (to soften the gripper while conforming to a target object or to release an object). The thresholds required to accurately translate user intent to gripper control can vary greatly between users. Therefore, a controller interface was included to manually tune each threshold using a potentiometer. Note that the pneumatic system was “closed” when no signals were active, such that vacuum levels were maintained even if no active “grip” signal was generated; a check valve was also included to limit the positive pressure in the system to prevent the PJTD from overinflating. All the functional system components are presented in Figure 3.

Figure 4 presents images of the assembled system (without the prosthesis attachment) on an able-bodied person. The pneumatic components were too large to be reasonably placed on the user’s arm, so most of the components were stored in a backpack for the user to wear.

Pneumatic and power components. Based on Liberating Technology, Inc.’s expertise of the prosthetic industry, as well as guidance from a prosthetist, our priorities were to design the PJTD to be portable and rapidly operated. In evaluating commercially available pumps, we considered pumps that were reasonably sized (i.e., could be carried by a person) and exhibit high maximum flow rates, metrics that are common when designing pneumatically controlled soft robotic systems.²⁰

Operation speeds were estimated using empirical flow rate versus pressure curves provided by pump manufacturers. The

cycle time required to change from pressure P_o to P_f was estimated numerically, where $P_i = \frac{n_i}{n_o} P_o$ and $n_{i+1} = n_i \pm \frac{dn_i}{dt} \Delta t$ (n is the number of moles of air, Δt is a small time increment, and i is an indexing variable). Using flow rate (dV/dt) versus pressure (P) data, the total cycle time was estimated using the time derivative of the ideal gas law, $P \frac{dV}{dt} = \frac{dn}{dt} RT$. This method was validated by comparing predicted cycle times with measured pressure versus time data for candidate pumps we had access to. Table 1 presents a comparison of candidate pump technologies that were selected to minimize size and weight while maximizing flow rate.

Keeping the grip/release cycle time close to that of current prosthetic terminal devices was a top priority in selecting the candidate solutions, the Parker T1-2HD-12-1NEA was selected for amputee testing. 11.1 V 5.0Ah polymer Li-Ion battery pack. For reference, the mass of the PJTD gripper distal to the socket was 920 g, and the Greifer and ETD were 544 and 522 g, respectively.

Control strategy. Initially, the control strategy was threshold based, where the grip and release channels had thresholds that rendered them active or inactive (bang–bang control for each channel). Early tests with an amputee subject indicated that cocontraction or premature contraction of the forearm muscles was an issue, especially when the user activated muscles to trigger a grip/release command while performing other load-bearing actions (such as pushing PJTD against an object to conform to it).

FIG. 3. Photos of the components of the PJTD system (without the prosthetic socket): (a) vacuum pump; (b) two solenoid valves; (c) check valve; (d) flow-control valve; (e) vacuum gauge; (f) box containing control board and battery; (g) controller interface; (h) jamming gripper body; and (i) Otto Bock quick disconnect attachment. Color images available online at www.liebertpub.com/soro

FIG. 4. Photos of the assembled PJTD system used in amputee testing: (left) the primary pneumatic and power components stored in a backpack and (right) an able-bodied user wearing the system while holding the jamming gripper. Color images available online at www.liebertpub.com/soro

TABLE 1. VACUUM- AND POSITIVE-PRESSURE-GENERATING TECHNOLOGIES CONSIDERED FOR THE PJTD ULA-COMPATIBLE PROTOTYPE

Vacuum source	Positive-pressure source	Appx. total cycle time, sec		Total pump weight, grams	Total size, cm
		Max. vacuum: 15 in Hg	Max. vacuum: 20 in Hg		
Venturi vacuum generator (through compressed air) ^a	Compressed air (<28 LPM into gripper) ^a	0.15	0.21	N/A	N/A
Parker T1-2HD-12-1NEA	Thomas 1420DP BLDC	0.18	0.39	1729	18×13×7
Parker T1-1HD-12-1NEA		0.33	0.70	1502	16.5×9.9×7
Thomas 1420VP BLDC ^b		0.81 ^c	1.80	380	Two of 7.5×7.2×2.9
Thomas 1420VP BLDC ^b		1.02 ^c	2.10 ^c	190	7.5×7.2×2.9

^aRequires off-board air supply; included for reference.

^bUsed in able-bodied tests.

^cEmpirically measured.

PJTD, prosthetic jamming terminal device; ULA, upper-limb amputee.

A differential control strategy that is commonly used in upper limb prosthetics was then utilized so that the dominant signal would drive the controller even in cocontraction.²¹ This strategy demonstrated better performance, but could take substantial time to calibrate to some users, and it was possible to create unintentional transitions from one state to another. To overcome this issue, the control strategy was restructured to intentionally introduce hysteresis, such that each desired state of PJTD had different entry and exit signal thresholds (e.g., a grip command would only be triggered if a certain threshold was reached and would be maintained until the signal dropped below a lower specified threshold).

Human subject testing was limited, and the control strategy was improved for each subject. Subjects were able to control the devices as desired during the testing, but the full hysteresis control strategy was only available for the final subject (later signified as subject A2).

Amputee testing methodology

Able-bodied participants reported that the length of the test sessions induced fatigue. Therefore, the test session was shortened for amputee testing: only the ETD was used in comparison with PJTD and only one UNB subtest (Subtest 1)

was used. The ETD was selected for comparison because it was the lower performing of the two commercial devices and would therefore represent a minimum viability benchmark for evaluating the market feasibility of the PJTD. The Greifer and ETD actually exhibit similar pinching speeds (~0.5 s from fully open to fully closed positions); however, the Greifer might have performed more rapidly in the MBB test because its parallel pinching surfaces could have enabled more efficient grips on the blocks.

Unlike during able-bodied test sessions, amputee subjects were given specified amounts of time and tasks to become familiar with the terminal devices to enable all subjects with the same level of familiarity with the technologies. The number of participants was limited due to the limited resources of this Phase I research; the findings presented here are for a pilot study only of the novel prosthetic device. Four individuals with unilateral transradial limb absence participated in the pilot study, although only two participants completed all tasks in the protocol (henceforth identified as subjects A1 and A2). The goal was to select participants who had no prior experience with the Greifer or ETD, although this was difficult to satisfy due to the limited group of available participants; subject A1 had experience with the Greifer, while subject A2 had experience with both devices.

FIG. 5. MBB test results for subjects A1 and A2 for the ETD and PJTD devices: (a) average completion times, (b) angular displacement of the shoulder joint from resting position, and (c) a screenshot from a video taken during an MBB test with an amputee subject using their contralateral hand to apply a load to PJTD to conform it against a test block. Color images available online at www.liebertpub.com/soro

FIG. 6. Shoulder and arm joint angles during the MBB test with picking up blocks. Color images available online at www.liebertpub.com/soro

Subject A1 had a left-side transradial amputation with an ~12-cm residual limb distal to the elbow. Subject A2 had a congenital limb absence on the left arm and a 6-cm limb distal to the elbow. Of the remaining subjects, one was unable to provide enough downward force with their short residual limb to utilize the PJTD and the other had a prosthesis without a QD wrist, which was required for interfacing with the terminal devices in this study.

Participants used their existing myoelectric sockets during testing. During each participant's test session, they performed three tasks with the PJTD and the ETD: (1) device training and controller calibration; (2) three MBB trials; (3) and UNB Subtest 1. This procedure was completed with one

device before using the second one, and the order of devices tested was randomized. Afterward, participants completed questionnaires for qualitative assessment of the devices.

During the MBB test, an inertial measurement unit (IMU) was mounted on the upper arm to record the angular displacement of the shoulder to gauge the degree of compensatory shoulder movement, as it was hypothesized that the axisymmetric design of the PJTD would decrease compensatory movement relative to other devices like the ETD.

Results

Figure 5 presents the MBB test results, including the IMU data. The subjects were able to complete the test with both devices, although they both completed the task more rapidly using the Motion Control ETD. Even though the PJTD vacuum pump enabled subsecond grip cycles comparable to the grip speeds of the ETD, users of the PJTD had to spend additional time conforming the gripper to the object before each grip operation.

As indicated in Figure 5, subject A1 demonstrated more shoulder compensation with the ETD than with the PJTD; in general, compared to subject A2, their shoulder was more elevated and protracted during the task (Fig. 6). Unlike subject A1, subject A2 took advantage of the wrist flexion feature in the ETD and angled it at 30 degrees; compared to A1, subject A2's modification to the alignment of the ETD might have improved the usability of the ETD in this task, resulting in similar and minimal shoulder compensation with both devices.

Table 2 summarizes the results of UNB test. Both subjects were able to complete all tasks with both devices, however, they functionally scored higher with the ETD. Scores with the ETD were comparable across subjects. Subject A1 had higher scores with the PJTD than subject A2 did.

Based on a questionnaire given at the conclusion of each subject's session, Table 3 presents each subject's preferred device for completing each task. Subject A2 preferred the ETD unanimously, while subject A1 preferred the ETD for

TABLE 2. UNB SUBTEST 1 FUNCTIONAL OUTCOME SCORES

Task	Subject: A1				Subject: A2			
	ETD		PJTD		ETD		PJTD	
	Spontaneity	Skill	Spontaneity	Skill	Spontaneity	Skill	Spontaneity	Skill
Carry milk crate of tools/wood across room(s)	4	4	4	4	4	4	4	4
Measure length of wood with and mark the middle	4	4	4	4	4	4	3	3
Place wood in a table vice	4	3	4	4	4	4	4	4
Hammer nail	4	3	2	1	3	3	4	4
Sweep up dust with handheld brush or regular broom & dust pan	4	2	4	4	4	4	3	3
Groom fingernails with nail file	4	4	4	3	4	4	4	3
Fold a letter and put it in the envelope	4	4	4	1	4	2	2	1
Chop up an apple (hard food)	4	4	4	2	4	4	3	2
Make kebabs alternating hard and soft foods	4	4	4	4	4	4	4	4
Put up an umbrella	4	3	4	2	4	4	4	3
Total	40	35	38	29	39	35	35	31

ETD, electric terminal device; UNB, University of New Brunswick.

TABLE 3. DEVICE PREFERENCE QUESTIONNAIRE RESULTS

Task	Subject: A1			Subject: A2		
	ETD	PJTD	No pref.	ETD	PJTD	No pref.
Carry milk crate	✓			✓		
Measure wood with tape	✓			✓		
Clamp wood to table			✓	✓		
Hammer nail	✓			✓		
Sweep dust with hand broom			✓	✓		
File fingernails	✓			✓		
Fold letter into envelope			✓	✓		
Chop apple with knife	✓			✓		
Make kebabs	✓			✓		
Open umbrella			✓	✓		
Pick up blocks			✓	✓		
Set blocks down			✓	✓		
See blocks around terminal device	✓			✓		
Pick up common objects	✓			✓		
Set down common objects			✓	✓		
Total preference (%)	53	0	47	100	0	0

roughly half of the tasks and had no preference for the remaining half. Subjects were also asked to provide qualitative feedback of the PJTD. All the written feedback is provided as follows: subject A1 indicated that the PJTD was fairly comfortable, a bit heavy, easy to use given it was their first time using it, and rated its overall performance as adequate. Subject A2 indicated that PJTD was uncomfortable because of the weight, difficult to control initially, and obstructed the user's view of target objects.

Fatigue was a drawback of the PJTD because unlike with a traditional "pinching" terminal device such as the ETD, users had to apply vertical loads to the PJTD to conform it to objects (Fig. 5c). Several methods were used to reduce fatigue, including softening the PJTD by slightly inflating it with positive pressure to enable it to more easily conform to objects and varying the orientation of the PJTD (e.g., perpendicular to the palmar or ulnar surface of the user) to decouple the muscles used to activate the myoelectric signals from those for pushing the PJTD against objects. In addition to qualitative feedback provided by participants, industry experts, including prosthetists and upper-limb prosthetic researchers, indicated that the size, weight, and noise (produced by the vacuum pump) of the system were too excessive to be feasible as a product. While the PJTD does provide some unique benefits over existing terminal devices, they are outweighed by the practical drawbacks of the system.

Discussion

We developed a PJTD prototype and tested it with a small group of ULAs in a pilot study. While the results were limited at this early stage of research and should not be used to represent the expected outcomes of the broader ULA population, they did provide significant insight into the near-term potential for applying soft robotic research to real-world applications. The process revealed several fundamental areas for improvement of the device concept, such as operations resulting in user fatigue, which can be improved with additional research into high-performance, lightweight granular materials, and further work on optimizing gripper shape to minimize gripper size.

However, the most limiting factor in preventing the PJTD from becoming a viable product was the lack of commercially available pneumatic technology that can enable rapid operation times while being small, lightweight, and quiet enough to be comfortably worn by a user in daily life. This is a common challenge for the field of soft robotics, where systems are often pneumatically controlled; many soft robotic laboratory-bench prototypes can exhibit large changes in volume, stiffness, and shape, enabling them with unparalleled potential to improve the capabilities in many areas, including manufacturing, medical devices, and search-and-rescue technologies. For applications in which these technologies need to operate untethered, such as for the PJTD, the required actuation and power components can still be several times the size and weight of the soft robotic body, countering the practical and functional benefits of the core soft robotic technology.

This is a critical roadblock in the path ahead for soft robotics that must be addressed to bridge the gap between the promise of this novel class of technologies and their ability to make a positive impact in the real world. Once pneumatic technology can be sufficiently flexible or miniaturized, then soft robotic systems such as the PJTD can be equipped to become viable technologies that may benefit many applications still hampered by the limitations of traditional robotic technology.

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