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研究課題名（和文） Parallel Elastic Tendons using Functional Fluid for Robotic Hands

研究課題名（英文） Parallel Elastic Tendons using Functional Fluid for Robotic Hands

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研究成果の概要（和文）：本研究では、パラレル・エラスティック・テンドン（Parallel Elastic Tendon、PET）の基礎特性・構造、又は装着型ウェアラブルロボット技術への応用を検討した。PETのブレーキ力の調整能力を縦型電動計測スタンドによる計測を行い、PETの現実のブレーキ力の調整能力が以前得られたシミュレーションの結果と同等となることを検証した。それにより、PETのモデル化が可能になり、より高度な制御方法が実施可能になる。①足首支援の短下肢装具、②腰支援外骨格ロボット、③義手といったデバイスに対して、一般的のアクチュエーターの代わりにPETの活用可能性を検証した。

研究成果の学術的意義や社会的意義

This work investigated and modeled a new type of semi-active actuators based on smart fluid technology (PET). We explored practical and affordable wearable robot technology; ankle foot orthosis and lumbar support robots, that could improve the health care and worker support technology in society.

研究成果の概要（英文）：During this project we investigated the basic properties and construction of parallel elastic tendons (PETs). We also investigated their application in wearable robotics: 1. Robotic ankle foot orthosis, 2. Lumbar support exoskeleton, and 3. prosthetic hand with a passive PET. The results showed that PETs can be an alternative to traditional actuators, or as a controllable link that improves the physical human-robot interaction.
In addition, we characterized the performance of PETs in terms of braking force regulation based on coil current and movement speed. The results showed the real-world performance of PETs to match the theoretical values derived from the earlier theoretical simulations. This verifies the design and development methods, and based on these measurement modelling of PETs will be viable for more sophisticated control methods.

研究分野： ロボティクスおよび知能機械システム

キーワード： mechanical linkage　assistive robots　elastic element

１．研究開始当初の背景

Series elastic elements and series elastic actuators can achieve compliance in wearable assistive robotics and robot-human collaborative tasks [1]. However, installing an elastic element in series with the actuator or the force transfer mechanism imposes permanent compliance that reduces the output bandwidth and accuracy.

２．研究の目的

The purpose of this project is to investigate parallel elastic tendons (PETs), opposed to series elastic elements, that can be controlled in terms of viscosity and energy storage. The PETs can be used as a semi-active component in a robotic device, they can replace a rigid link in a linkage mechanism to achieve new compliant behavior, and they can be used in combination with an actuator.

The original purpose of the project was to investigate PETS in robotic hands and grippers. However, due to issues in miniaturizing the PET to a size suitable for robotic hands, the purpose was updated during the project to investigate their function in wearable robotics such as a robotic Ankle-Foot-Orthosis (AFO) for persons with drop-foot syndrome, and a lower back support exoskeleton for factory and care giving workers.

３．研究の方法

The project consists of three research steps: ① simulation and development of PETs, ② measurement of PETs properties, ③ development and investigation of applications based on PETs.

In this project we developed two versions of PETs: small version (90x16.5mm, 200-300N braking force) and a large version (111x23mm, 500-900N braking force). The smaller version is suitable for applications such as ankle support and elbow support robotic orthoses, and the larger version is suitable for applications such as back support robotic exoskeletons, knee support robotic orthoses, and knee joint for prosthetic legs.

４．研究成果

First, we will revise the definition of a PET based on the work conducted in this project. A PET is a linear joint that utilizes Magneto-Rheological (MR) fluid and a compression spring to achieve controllable compliance. The MR fluid is a smart fluid that can change its apparent viscosity in response to a magnetic field. With no magnetic field the MR fluid displays low viscosity, and with incremental magnetic field the viscosity increases up to a saturation point. MR fluid based controllable dampers have been used in the automobile industry, in electrical appliances, and in wearable robotics such as AFOs and prosthetic legs as well. The approach used in this project differs from other works in three points:

1. The PET utilizes the property of the MR fluid in combination with a compression spring. Thus, the joint displays both viscosity and stiffness properties. The spring stiffness is not controllable, but different springs can be used based on the intended task at the time of assembly.
2. The PET is designed to be clutch-able. The maximum braking force of the PET is designed to be considerably higher than the spring stiffness, and the external force acting on the PET from the load. Therefore, the PET can function as a compliant link in the system, or as a rigid link when fully clutched.
3. Because of the above two properties, the PET can also function as an energy store-and-release device. i.e. when kinetic energy received from the load acts on a PET it compresses the internal spring, the PET then can be clutched to store this energy, which can be release later by unclutching the PET.

* Outcome 1: development of PETs

The two PETs were developed in the Artificial Intelligence Laboratory, University of Tsukuba. The larger iteration is an improvement of a previous iteration developed in the same institute. It is named MRLink Z. The smaller version is developed entirely within this project, it is named MRLink Slim. The code name MRLink means MagnetoRheological Link, which denotes the smart fluid used in the device, and its function as a mechanical link. The MRLink mini shown below is still under development.

MRLink Slim
Size: 89*16.5mm
Spring: 4.41 N/mm
Coil: 3.2 Ohm

MRLink Z
Size: 111*23mm
Spring: 12.26 N/mm
Coil: 6.2 Ohm

MRLink mini
Size: 34*10 mm
Spring: tbd
Coil: tbd

* Outcome 2: measurement of PETs properties

To measure the PETs properties, we devised a measurement setup composed of a motorized vertical force-displacement measurement stand from IMADA corporation (MX2-2500N-FA), equipped with force gauge (ZTA-2500N) and a linear displacement encoder. The PETs were fixed to the base of the force measurement stand with 3D printed parts, and force was applied vertically on the interaction rod using the force gauge. A power supply was used to apply currents in the PETs' coils.

The braking force is regulated by the interaction speed (viscosity) and by the coil current. Therefore, the measurements for each of the two prototypes were repeated for coil currents 0-1.1 Amp at 0.1 Amp intervals, and for speeds of 1-5mm/s at 1 mm/s intervals. The coil current is limited by the maximum tolerance ampere of the coil, and the speed is limited by the maximum speed of the motorized test stand.

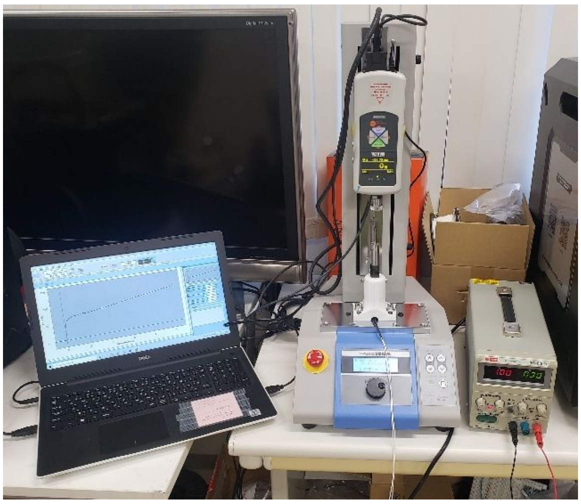


Figure 1. The setup used for measurement of PETs properties. Vertical Motorized Test Stand, Force gauge, power supply, and measurement computer.

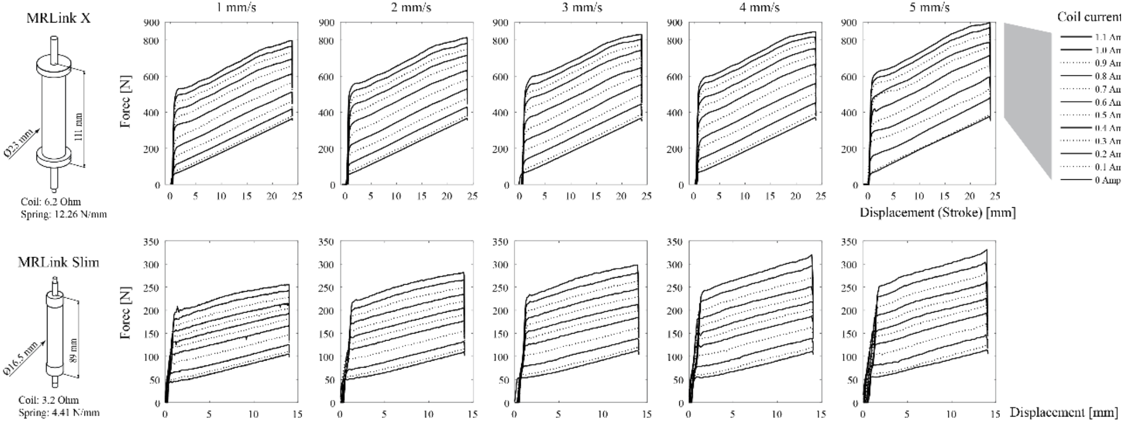


Figure 2. Results of PET braking force measurement.
Top, MRLink Z, coil current from 0 to 1.1 Amp, interaction speed 1-5mm/s.
Bottom, MRLink Slim, coil current from 0 to 1.1 Amp, interaction speed 1-5mm/s.

* Outcome 3: Applications based on PETs

In this project two applications were investigated based on PETs, a robotic AFO for persons with drop foot syndrome, and a robotic exoskeleton for lower back support. We also investigated a passive PET made with 3D printed material in a prosthetic hand. In this case the PET served a beam spring that enhances the grip on the manipulated object, and improve the variety of handleable objects, e.g. bowl-shaped kitchenware.

1. Robotic AFO with elastic tendon [2]: A robotic AFO, named SmartAFO has been investigated in the Artificial Intelligence laboratory for several years. With the development of MRLink Slim in this project SmartAFO was updated with this new component. This reduced the weight of SmartAFO by 200 grams and improved the maximum braking force from 90N to 200N approximately. Clinical experiments with persons with drop-foot syndrome are planned in Ichihara Hospital (Tsukuba City, Ibaraki, Japan.). However, the clinical tests are currently delayed due to the COVID-19 pandemic and will be resumed later when safety can be insured.

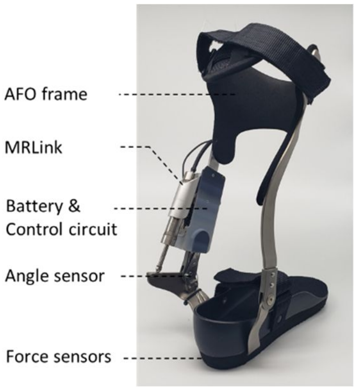
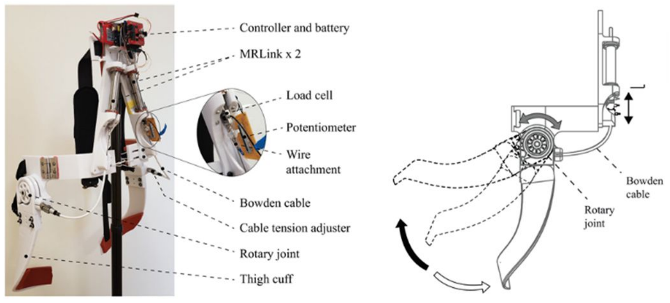


Figure 3 Updated SmartAFO with the PET developed in this project.

2. Lower back support exoskeleton [3]: A lower back support exoskeleton was developed based on the larger version of the PET; MRLink Z. The exoskeleton uses two PETs to provide additive braking at the hip joints when lowering a weight, stores energy in the compression springs when putting down the weight and uses the spring energy to assist the lift motion when lifting the weight. The PET’s linear movement is converted to rotary movement at the hips using a Bowden cable and CAM mechanism. The exoskeleton was tested at the university of Tsukuba Hospital with healthy persons. The experiment showed a reduction in the latissimus dorsi (LD) muscles activity when using the exoskeleton compared not using the exoskeleton.



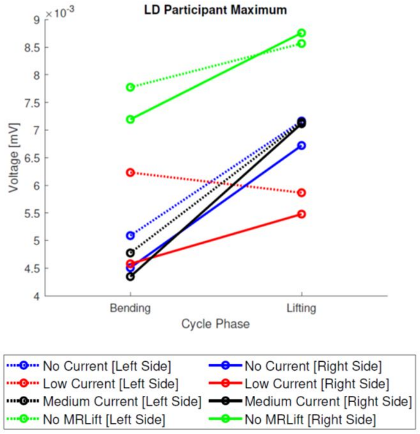


Figure 4. Left: Components and articulation of the lower back support exoskeleton. Right: LD muscle activation with/without the exoskeleton.

3. Passive PET application in prosthetic hands [4]: Although it was not possible to embed PETs in prosthetics hands within this project, we investigated the use of a passive PET in a prosthetic hand. We devised a PET from 3D printed material in the shape of a hook which functions as a beam spring and used it as a support structure for holding kitchenware. With the prosthesis a user was able to hold bowl kitchenware and perform other tasks.

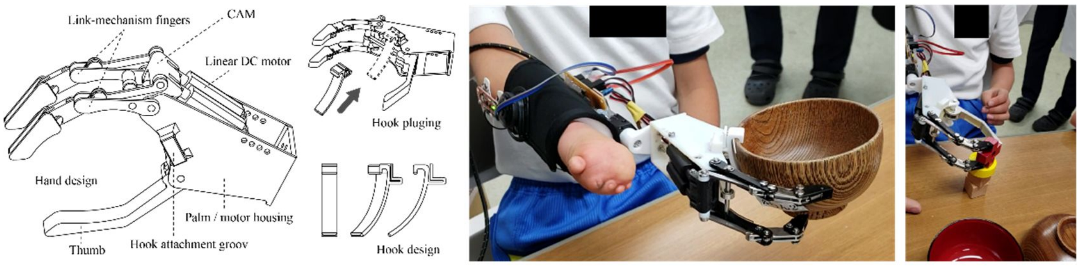


Figure 5. passive PET in prosthetic hand application.

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2. M. Hassan et al. Optimized Design of a Variable Viscosity Link for Robotic AFO, Proceedings of the 41st IEEE EMBC, pp.6220-6223, Berlin, Germany, July 23-27, 2019.
3. M. Hassan et al. MRLift: a Semi-active Lower Back Support Exoskeleton based on MR Fluid and Force Retention Technology, Proceeding of the 2019 IEEE/RSJ IROS, pp.7349-7354, Macau, China, November 4-8, 2019.
4. Modar Hassan et al. Prosthetic Hand with Hook-Plugin for Holding a Rice Bowl, World Congress of the International Society for Prosthetics and Orthotics, 2019, Kobe, Japan.

５．主な発表論文等

〔雑誌論文〕　計2件（うち査読付論文　2件／うち国際共著　2件／うちオープンアクセス　0件）

１．著者名 Hassan Modar、Kennard Maxwell、Yagi Keisuke、Kadone Hideki、Mochiyama Hiromi、Suzuki Kenji	４．巻 1
２．論文標題 MRLift: a Semi-active Lower Back Support Exoskeleton based on MR Fluid and Force Retention Technology	５．発行年 2019年
３．雑誌名 2019 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)	６．最初と最後の頁 7349-7354
掲載論文のDOI（デジタルオブジェクト識別子） 10.1109/IROS40897.2019.8967819	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

１．著者名 Hassan Modar、Yagi Keisuke、Kadone Hideki、Ueno Tomoyuki、Mochiyama Hiromi、Suzuki Kenji	４．巻 1
２．論文標題 Optimized Design of a Variable Viscosity Link for Robotic AFO	５．発行年 2019年
３．雑誌名 2019 41st Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)	６．最初と最後の頁 6220-6223
掲載論文のDOI（デジタルオブジェクト識別子） 10.1109/EMBC.2019.8856773	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

〔学会発表〕　計1件（うち招待講演　0件／うち国際学会　1件）

１．発表者名 Modar Hassan
２．発表標題 Prosthetic Hand with Hook-Plugin for Holding a Rice Bowl
３．学会等名 World Congress of the International Society for Prosthetics and Orthotics（国際学会）
４．発表年 2019年～2020年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

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６．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

７．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関