Research Article

Modular multi-motor exercise system for space exploration

José Baca[1] · Michael Martinez[1] · Scott Coles[1] · Andrew Garcia[1] · Donnie Berthelot[1] · James McCumber[1] · Tristan Norton[1] · Juan Torres[1] · Mussie Negash[1] · Minh Pham[1]

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Abstract
The goal of this project is to develop new technology that will support crew health and performance during long duration space missions. While there are current methods for maintaining fitness aboard the International Space Station, the results are not ideal; muscle mass and bone density continue to degrade, and there is still room for improvement. Moreover, new exploration missions need to maximize the use of the equipment due to storage limitations. A system that can be used for multiple purposes such as for providing multiple strength training exercises, as well as, providing aerobic exercises while using the same workout space is desirable. This project aims to address these challenges by introducing a modular system that will bring versatility, scalability, and robustness, by using mountable and reconfigurable modules to maximize the number of exercises that can be performed. In this paper we present the development of a Modular Multi-Motor Exercise System concept based on Magneto-Rheological fluid-based modules.

Keywords Modular systems · Space exploration · Exercise device · Magneto-Rheological fluid

1 Introduction

While living and traveling in microgravity environments such as in space or at the International Space Station (ISS), the human body uses significantly less muscles to move around on a daily basis. The astronaut faces no gravitational forces acting on muscles and joints, causing loss of muscle mass, bone density, and aerobic conditioning. Without regular exercise, muscles weaken and deteriorate causing muscle atrophy. Studies have shown that astronauts experience up to a 20% loss of muscle mass on spaceflights lasting 5 to 11 days [13, 25]. Muscle atrophy means a loss of strength, which is dangerous if a crew member has to perform a task either on-orbit or upon re-entry into the Earth's gravitational field. Therefore, maintaining muscle in space is critical, and is combated by current exercise countermeasure devices such as ARED (Advanced Resistive Exercise Device), CEVIS (Cycle Ergometer with Vibration Isolation System), T2 treadmill and MED-2 (Miniature Exercise Device-2) [19]. It is important to highlight that recent studies have shown little impact on loss of muscle tissue during prolonged space flights [26]. Additionally, due to the microgravity nature at ISS, exercise devices have unique design challenges which increase their mass and volume (compared to Earth's devices). For upcoming missions, some of the crew health and performance challenges are to reduce mass and volume of exercise devices (due to small footprint limitations within spaceship), to fulfill performance requirements (i.e., to be able to perform strength training and aerobic exercises), and to increase safety during human-machine interaction.

1.1 Objective

This work addresses the problem of maximizing the number of different resistive and aerobic exercises that can be performed with a single system and within a small footprint. Our proposed solution is based on the modularity

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✉ José Baca, jose.baca@tamucc.edu | [1]Department of Engineering, Texas A&M University-Corpus Christi, Ocean Dr., Corpus Christi, TX 6300, USA.

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concept and brings benefits such as versatility, robustness and scalability to the tasks. A Modular Multi-Motor Exercise System that can both, (1) rearrange their modules to adapt to different upper body and lower body parts, and (2) provide strength training and aerobic exercises, makes it ideal for this challenge in space. To increase safety of crewmembers during execution of the exercises, Magneto-Rheological fluid has been explored as main component in the design of the modules (elemental unit of the system). In Sect. 2, we describe different types of actuators that are currently used for a variety of purposes, particularly, the ones that could be used for space applications. Section 3 introduces the Modular Multi-Motor Exercise System concept along with the design criteria, benefits, and a set of resistive exercises that are currently performed at ISS that target different muscle groups. Section 4 describes the main element of the system, the module, which is based on Magneto-Rheological Fluid. We present two prototype modules that can control magnetic fields in a different manner, i.e., Electromagnet-Triggered Control and Switchable Magnet-Triggered Control. To validate their performance, in Sect. 5, we describe a set of experiments used to analyze their performance such as resistive forces generated by each module along with corresponding energy consumption. In Sect. 6, we discuss the results and indicate advantages and disadvantages of utilizing both modules. We address how this system could be improved to fulfill better the specified requirements.

2 Related work

In order to maintain the astronauts' fitness, different exercise systems have been designed to work in a microgravity environment, for instance ARED, CEVIS, T2 and MED-2. Each system works differently due to the design and operation of its main actuator. For instance, ARED allows the user to execute resistive exercises by simulating free weights. This resistive force is generated by two actuators that are based on a piston-cylinder assembly with an adjustable load, and employs vacuum cylinders to deliver a constant resistance, and a flywheel to change the resistance. As a second example and one of the latest devices to be designed, MED-2, is based on a series elastic actuator (motor that controls a pulley), which tensions an exercise cable, and provides resistance as the user pulls the cable. For the challenge presented in this work (exercising the human body in space), parameters such as the microgravity environment, the size of the equipment, the energy consumption and the safety of the user when interacting with the equipment, should be taken into consideration when designing the system. Therefore, the selection of the main actuator of the system will greatly impact these parameters. For instance, electromechanical actuators can offer the same strength of hydraulic actuators but with higher precision and better control of the motion. They are a popular alternative for robotic and other applications. DC motor-based actuators have shown to be very effective when using them in robotic assistance and rehabilitation purposes. Safety can be implemented by limiting the output torque and by implementing control techniques to limit range of operation. This requires continuous monitoring of the actuator. Power consumption has been observed to be reasonable, with relatively medium to high voltage inputs (up to 230 V in some models) [5, 8, 9, 14, 22]. Another alternative is the use of Dielectric Elastomer-based actuators (DEA). They are based on soft materials that deform under the presence of large electric fields. Proper control of DEA deformations has been demonstrated by using different materials and by using simple geometric shapes (e.g., inchworm shape). It has been observed that the actuation forces are not enough to lift large loads. For their operation, it has a required voltage of about 1kV and up, which not only drastically increases power consumption but also makes safety difficult to implement [6, 10, 16, 23, 33]. Another actuator option is the use of Magnetic-based actuators. They make use of a polymer gel embedded with iron particles and it is activated by the presence of an external magnetic field. Research has shown that the magnetic particles have the ability to stay static within the polymer gel, allowing the deformation of the entire gel volume, which can potentially be used to provide a force [7, 11, 12, 15, 27, 29, 31]. One more option is the use of Rheological Fluid-based actuators. They are based on smart fluids that exhibit variable viscous properties depending on external stimuli. There are two major types of Rheological Fluids, i.e., Electrorheological Fluid (ERF) and Magnetorheological Fluids (MRF). ERF is electrically activated and has shown to be affected by changes in the temperature and requires high voltages for its operation (average of 5 to 7 kV/mm^2). MRF, on the other hand, operates with magnetic fields. The use of magnetic fields can not only reduce power consumption but also make the system feasible to work in space, reason why we have decided to explore it [4, 18, 20, 24, 28].

3 Modular multi-motor exercise system

This project aims to develop a system that can be used to perform several resistive and aerobic exercises while using the same space, therefore, reducing size and mass of current ISS equipment. To address the problem, we explore a new type of strategy via modular design [1, 2]. The system consists of homogeneous modules that can be assembled and disassembled around a platform (cage-like frame that

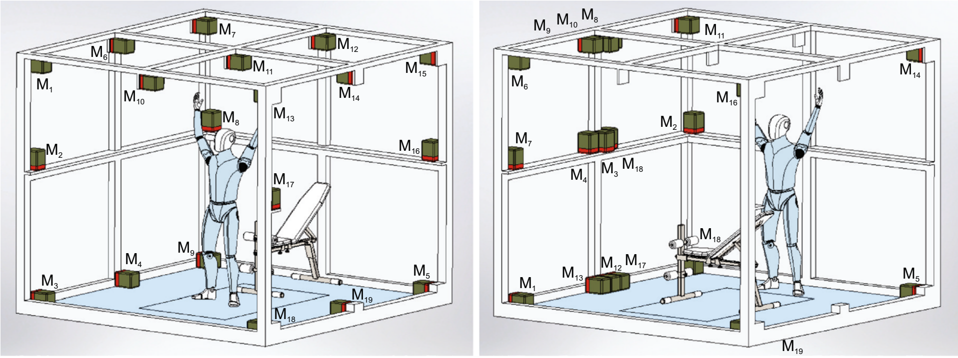


Fig. 1 Modular multi-motor exercise system

can eventually be attached to the current Vibration Isolation System) by crewmembers to workout different muscle groups. For example, Fig. 1 displays two potential modular configurations that a single crew member can assemble to target different muscle groups with different forces for a variety of strength training and aerobic exercises. The main principle underlying the modularity concept is that a system consisting of modules can create different configurations to deliver diverse performance characteristics. Design and operation of the module is presented in Sect. 4.

Each configuration is suitable for exercising different upper body and lower body muscle groups regardless of limb length. The concept must consider the following criteria designs:

- Modularity—Develop a concept that will maximize the number of different resistive and aerobic exercises.
- Smaller footprint—Payload inside spacecrafts are limited by size and weight, therefore, it is required to accommodate a compact exercise device with similar functions and capabilities of current ISS exercise devices.
- Performance requirements—System should be able to provide high loads at low frequency and lower loads at higher frequency, by indicating path to scalability.
- Range of motion and height requirements—System must meet height requirements and ranges of motion that allow for their usage in different exercises. It should be able to accommodate average female/male height and range of motion.
- Safe operation—System must operate with safety as a priority.

3.1 Resistive exercises for different muscle groups

Resistive exercises are one of the countermeasures to muscle atrophy during exposure to microgravity. A resistive exercise is any exercise that causes muscles to contract against an external resistance with the expectation of increases in mass, strength, tone, and/or endurance [3, 21, 30, 32]. The proposed modularity concept will bring users a versatile workout space that could adapt to different workout routines that include target exercises for all muscle groups, strength training, and aerobic exercises, as shown in Fig. 2.

For instance, Fig. 2a displays a configuration that can be used to exercise the lower body muscles by performing a squat routine. Each module, by means of a cable, is connected to a common bar. Each module produces a resistive force when pulling the cable, and retracts cable when releasing. Another example is shown in Fig. 2b. This configuration can be used to exercise upper body muscles, for instance, the user performs a tricep extension routine by connecting modules to a single double D handle. The system can also be used for aerobic exercises, as shown in Fig. 2c. A floor door can be lifted to access the treadmill; by connecting modules to the sides of a conveyor belt, a manual treadmill is created. Similarly, a stationary bicycle could also be assembled by attaching modules to a set of pedals. In both examples, it is possible to reach various levels of resistance by changing module's parameters. Cables attached to a vest will be used to hold the user down on both examples, similar to the one used in current devices at ISS. Current exercises that are being performed with equipment at ISS are listed in Table 1 for upper body exercises, Table 2 for lower body exercises, and Table 3 for total body exercises.

4 Magneto-rheological fluid based module

Homogeneous modules will have the capability to be mounted on a frame in a variety of ways. This feature brings versatility to the system and capability to create different configurations for a wide variety of resistive exercises. The resistive force generated by a module is based on increasing/decreasing the viscosity of the Magneto-Rheological fluid (MRF) upon the presence of magnetic flux density. Two prototypes have been designed and

Fig. 2 **a** Configuration for lower body exercises: squat routine. **b** Configuration for upper body exercises: tricep extension routine. **c** Configuration for aerobic exercises

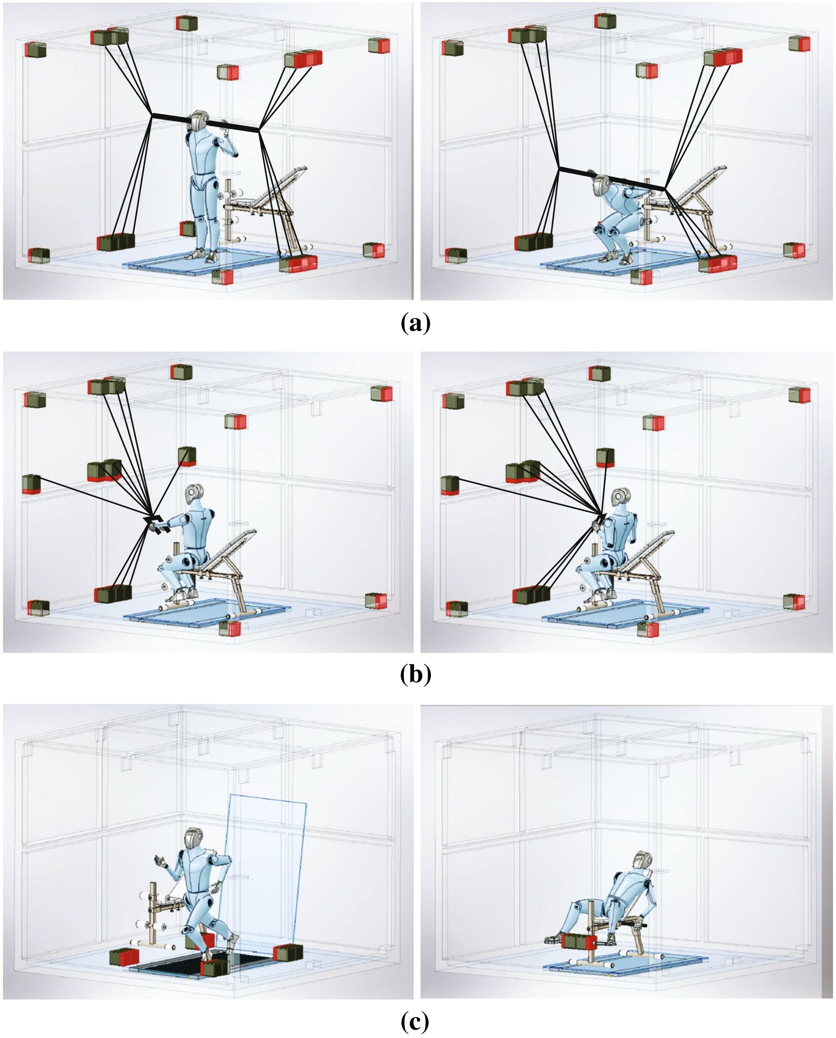


Table 1 Upper body resistive exercises—exercised muscle groups [17]

Upper body exercises	Major muscle groups
Bent over row	Latissimus Dorsi, Teres major, Rhomboids, Trapezius, Deltoids
Shoulder shrugs	Trapezius
Front shoulder raise	Deltoids, Trapezius, Rhomboids
Lateral shoulder raise	Deltoid, Trapezius, Rhomboids
Rear shoulder raise	Deltoids, Trapezius, Rhomboids
Bench press	Pectoralis, Deltoid, Triceps
Shoulder press	Deltoids, Triceps, Trapezius
Upright row	Deltoids, Supraspinatus, Elbow Flexors, Biceps Brachii and Brachialis, Trapezius
Tricep extension	Triceps Brachii, Posterior Deltoid, Rhomboids
Bicep curls	Biceps Brachii, Brachialis, Brachioradialis
Side bends	Obliques, Abdominal, Erector Spinae
Lateral neck extension	Sternocleidomastoid, Sternohyoid, Splenius Trapezius
Neck flexion	Sternocleidomastoid, Sternohyoid, Trapezius
Neck extension	Sternocleidomastoid, Splenius capitis, Trapezius
Crunches/sit ups	Abdominals

developed to analyze their performance and limitations, the first prototype being electromagnet-triggered controlled, and the second being switchable magnet-triggered controlled.

4.1 Prototype 1: electromagnet-triggered control

This prototype module is composed of two electromagnets (which is the source of the changing magnetic flux density) that will modify viscosity of the MRF. They are placed on the top and bottom part of the module to directly excite the MRF, which is located at the center of the module (7.5in × 7.5in, 9.12lbs), as shown in Fig. 3a. A propeller connected to a spring reel rotates along its shaft axis within MR fluid. The user spins the propeller by pulling a grip handle that is attached to cable and connected to spring reel, as shown in Fig. 3b. When electromagnets are activated, depending on the voltage (0–24V), the system will generate different resistive forces. The actuation force is proportional to the relationship between magnetic flux density and MR fluid. To select electromagnets, simulations in the magnetic flux density spatial variation for specific electromagnets were

Table 2 Lower body resistive exercises—exercised muscle groups [17]

Lower body exercises	Major muscle groups
Squats	Quadriceps, Gluteus muscles, Hamstrings
Deadlift	Erector Spinae, Latissimus Dorsi, Trapezius, Quadriceps, Hamstrings, Gluteus muscles
Heel raise	Gastrocnemius, Soleus
Hip adduction	Gracilis, Adductors, Longus, Brevis, Magnus
Hip abduction	Gluteus maximus, minimus, Tensor Fasciae latae
Hip extension	Gluteus maximus , Gracilis, Stmitendinosus, Biceps Fermoris, Semimembranosus
Hip flexion	Iliopsoas, Pectineus, Adductor Longus, Sartorius, Tensor Fasciae Latae, Rectus Femoris

Table 3 Total body resistive exercises—exercised muscle groups [17]

Total body exercises	Major muscle groups
Thruster	Quadriceps, Gluteus muscles, Hamstrings, Deltoids, Triceps, Trapezius
Swings	Quadriceps, Gluteus muscles, Hamstrings, Deltoids, Triceps, Trapezius, Deltoids, Rhomboids, Erector Spinae
Sumo Deadlift High Pull	Erector Spinae, Latissimus Dorsi, Trapezius, Quadriceps, Hamstrings, Gluteus, Deltoids, Supraspinatus, Elbow Flexors, Biceps Brachii and Brachialis

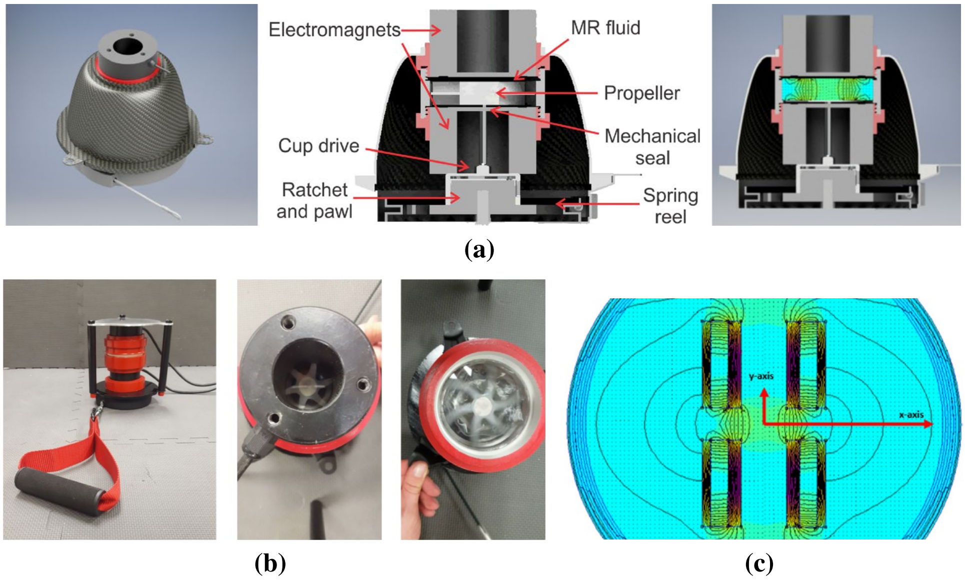


Fig. 3 Prototype 1: **a** 3D model and internal components. **b** Electromagnet-Triggered control. **c** Simulation of doughnut shaped electromagnets to determine the optimal distance apart

performed (FEMM 4.2). Results display best performance when using electromagnets with doughnut geometry at a optimal distance, as shown in Fig. 3c.

4.2 Prototype 2: switchable magnet-triggered control

The second prototype module (6.75in × 9.5in, 3.76lbs) follows similar design concept as in the previous module, as shown in Fig. 4. The main difference is that the electromagnets have been substituted by a single switchable magnet with the goal to reduce power consumption from the electromagnets which require approximately 25 W to operate. Since prototype 1 consists of two electromagnets, there is a power consumption of 50 W. On the other hand, switchable magnets are based on dipole magnets (one on top of the other) and require no power to keep its magnetic state; by rotating the upper magnet 180 ° will bring magnets into pole alignment, allowing magnetic flux to flow on a path outside the device. This feature creates two magnetic states, ON and OFF states. During the simulation analysis, planar symmetry was chosen to best model the dipole magnet.

5 Experimental results

In this section, we describe experiments done with both module prototypes to validate their performance. The set of experiments has been divided into 3 main cases: (1) set of pulling repetitions, (2) pulling and holding for 10 s, and (3) the power consumption analysis among prototypes. The goal is to demonstrate that the resistive force of the device increases with the increase of magnetic fields around the vessel, and to show the amount of resistive force achieved by prototypes. Prototype 1 utilizes two large DC ring electromagnets on top and bottom of the container to provide the desired magnetic field strength, as shown in Fig. 5a. The electromagnets are connected to a DC Power Supply that is used to set different voltage levels (0-24V) and provide current level values that will be used for data collection. Prototype 2 does not require a power supply because it is based on a switchable magnet, that can be manually rotated to an OFF/ON position (OFF–no magnetic field, ON—maximum magnetic field), as shown in Fig. 5b.

To measure the resistive forces, a one-dimensional force sensor is used to gather data in real time during the process of each exercise. To ensure accurate data from the force sensor, it is zeroed to an offset before applying a load and then calibrated using weights of a known value. After the force sensor is calibrated, it is placed between module's workout cable and grip (e.g., D-handle strap), as shown in Fig. 5. Using the Variense software, force sensor communicates at a rate of 9600 bps, each experiment is recorded, and plotted in MATLAB. Experimental components are summarized in Table 4.

5.1 Case 1: pulling repetitions

For this type of experiment, we analyze the resistive forces of both prototypes for pulling repetitions. The exercise was conducted by setting the module down, securing it to the top of a table, connecting the force sensor to a computer, then pulling on the cable directly away from the module. The cable was pulled with equal time (2 s) during the concentric and eccentric muscle movements to ensure consistency throughout the graphs. This process was utilized for both prototypes, as depicted in Fig. 5c, d, respectively.

The first prototype was tested at each voltage level, starting at 0V with increments of 5V, up to its maximum at 24V, for a total of 6 experiments i.e., 0V, 5V, 10V, 15V, 20V and 24V. It is possible to observe within experimental results increments of resistive force when increasing voltage, as shown in Fig. 6. Prototype 1 has the capability of producing a total of 6 levels of resistive forces, from a base resistance of 2 lbs at 0V, to a resistive force of 5 lbs at

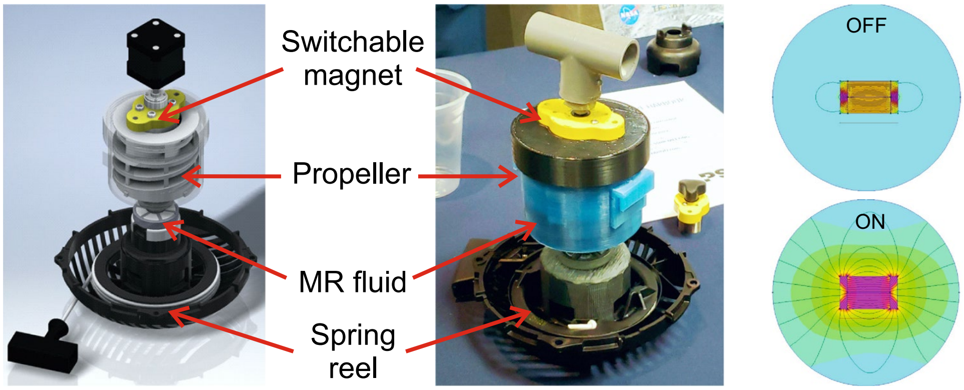
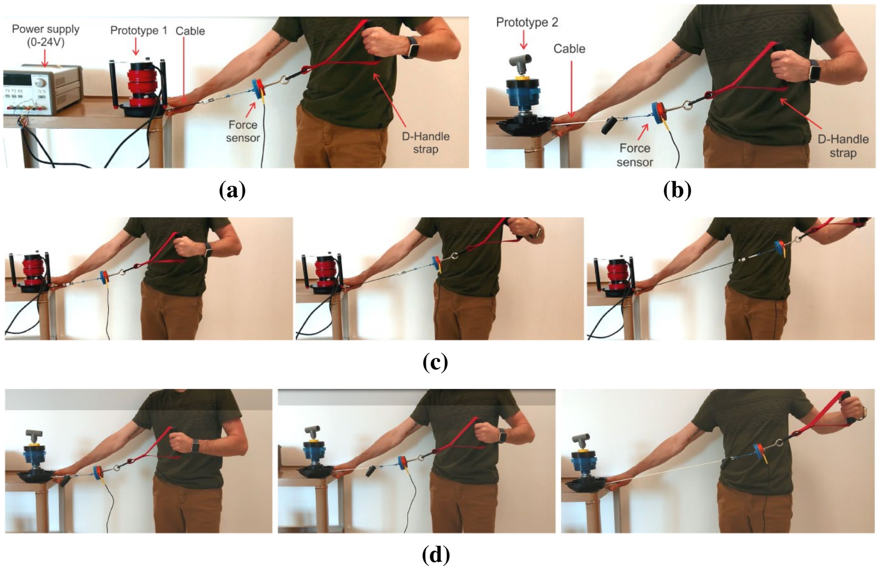


Fig. 4 Prototype 2: this module controls the magnetic fields by means of a switchable magnet. During the ON state, simulations results display a max of 0.34 Tesla, while the OFF state displays a max of 0.034 Tesla

Fig. 5 **a**, **b** The setup for both prototypes in which the experiment was conducted for each case. **c** Prototype 1 being pulled from start to finish. **d** Prototype 2 being pulled from start to finish



24V. Prototype 2, due to its design, two levels were tested (OFF/ON position), for for a total of 2 experiments. Results are shown in Fig. 7. Prototype 2 has the capability to produce 1.5 lbs of resistive force when switchable magnet is in the off position, and maximum of 2.5 lbs of resistive force when switchable magnet has the on position.

5.2 Case 2: pulling and holding

In this experiment, the handle connected to the cable on the module is being pulled, then held for a duration of 10 s, and then released. This exercise is being performed in both prototypes and resistive forces are shown in Fig. 8. It can be observed that each test reaches similar forces as in previous case, with the only difference being that resistive forces decrease by 0.5 lbs after a few seconds of holding the handle. Both prototypes are capable of generating corresponding forces for the different levels.

Table 4 Experimental components

Device name	Specifications	Purpose
DC ring electromagnets	2 units, 300-pound holding value, 24 V max, part no. D-302015-24	Provides the controlled magnetic field for the electromagnet prototype
DC power supply	Agilent E3631A, 25 V max, 1 A max	Provides variable levels of voltage to the electromagnets (0-24V)
Switchable magnet	Magjig 150, 150-pound holding value	Provides the controlled magnetic field for the switchable magnet prototype
Force sensor	Varriense FSE1001, 250 Newton max, and FSE-1 Reader	Gathers resistive force data in real time during the process of each exercise

5.3 Case 3: power and energy consumption

We now evaluate power and energy expended by prototype 1 and prototype 2 during the operation of an exercise routine. Prototype 1 has the capability of achieving six resistance levels, like the ones evaluated in the previous cases, which require increasing values of voltage. We will use these values given by the power supply to calculate power and energy consumption. The current draw values do not change while the device is being used, so it is assumed that this value remains constant throughout our calculations. Voltage levels were set and power and energy consumption were evaluated with Eqs. 1 and 2, respectively.

$$P = V * I \tag{1}$$

where P is Power (W), V is Voltage (V), and I is current (A). The equation used for energy consumption is:

$$Wh = P * Time(hrs) \tag{2}$$

where Wh is Watt-hours, P is Power (W), and Time is measured in hours. This value is taken from the total amount of

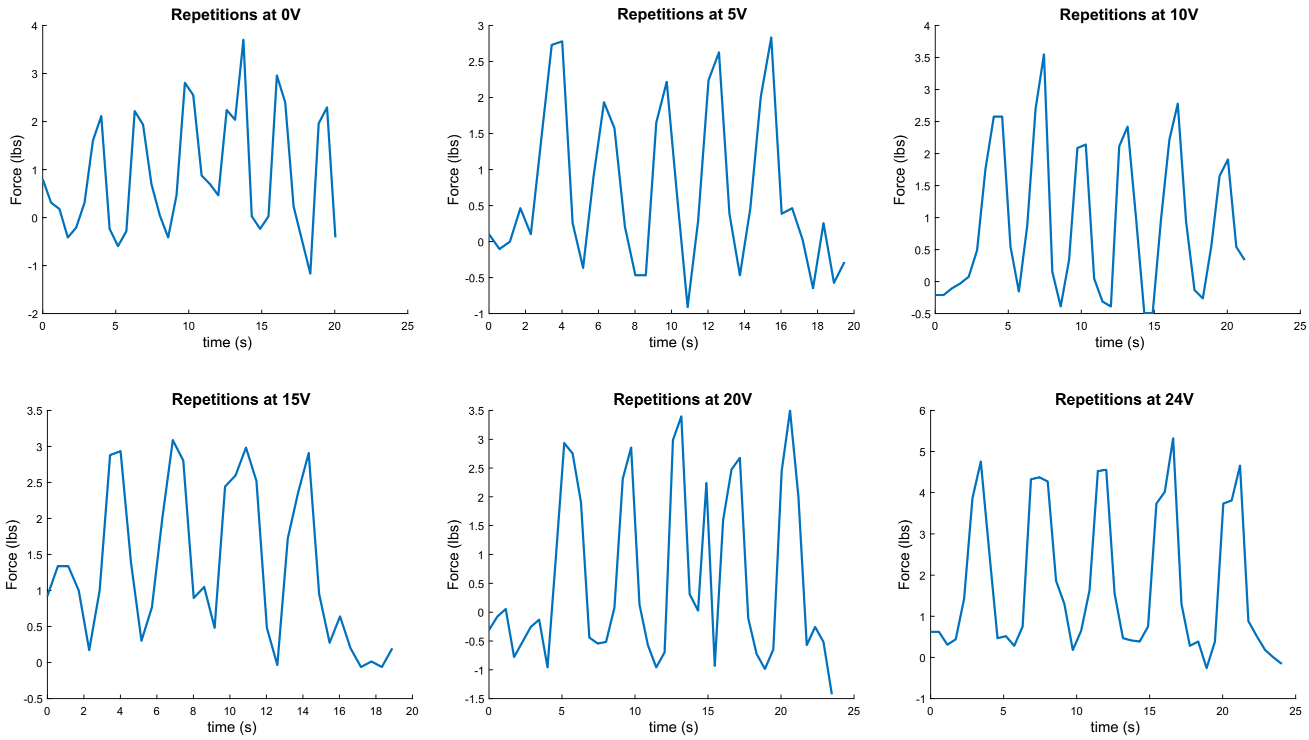


Fig. 6 Resistive forces generated by Prototype 1 during experiment at 6 voltage levels

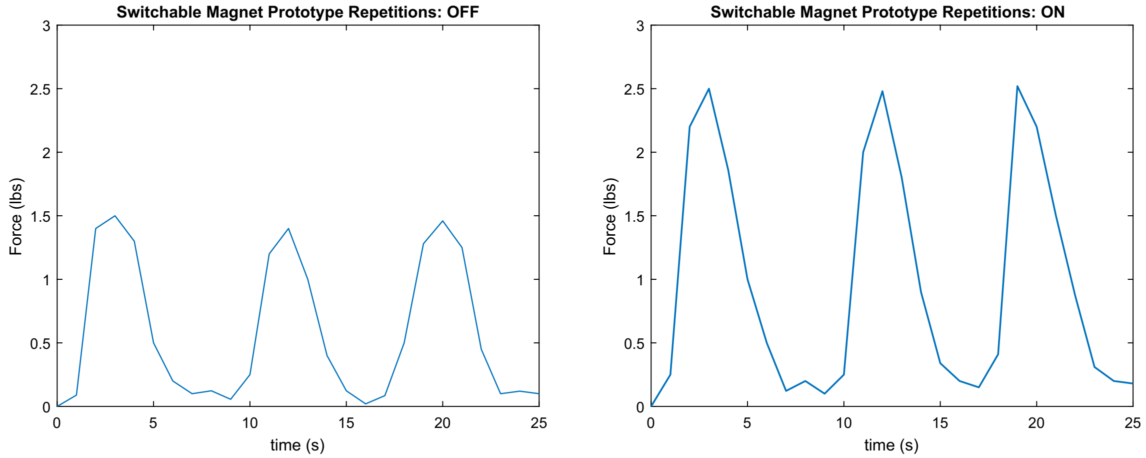
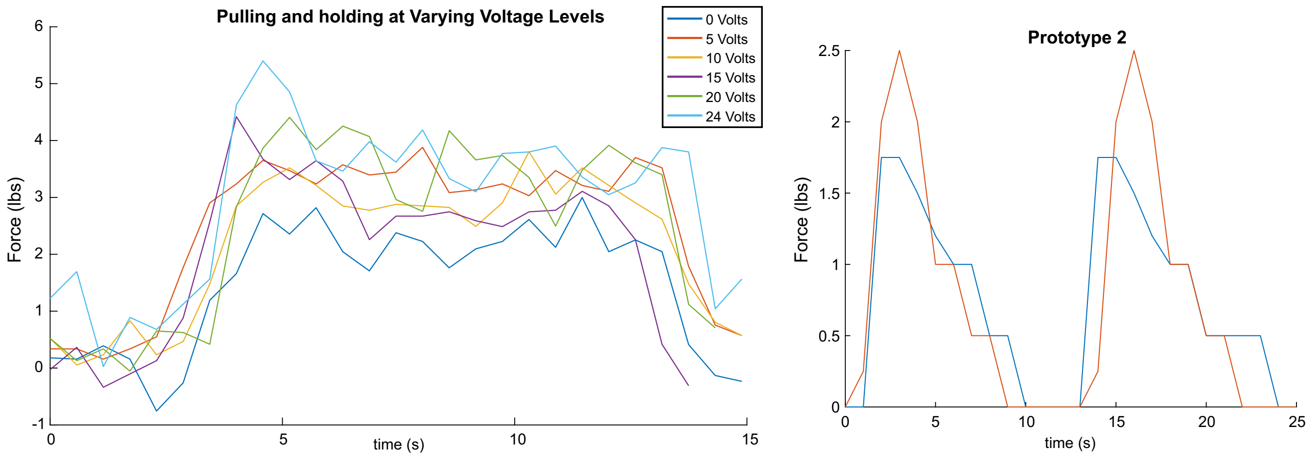


Fig. 7 Resistive forces generated by Prototype 2 during experiment at two states (OFF/ON)

time that a module is turned on. In this study, we assume the module will be powered for a period period of 2 h, which is the average time per day required for working out at ISS.

Table 5 summarizes the relationship between 6 resistance/voltage levels and their corresponding power and energy consumption values, as shown in Fig. 9.

Prototype 2 has two levels of resistance, one for when the device is off and another for when the device is turned on, and neither level of resistance requires power. Current method for inducing magnetic field within module's vessel to increase level of resistance is by manually rotating the switchable magnet. Therefore, no energy is required to activate it and produce resistive forces.



(a) (b)

Fig. 8 **a** Prototype 1: pulling and holding exercise among 6 voltage levels. **b** Prototype 2: comparison between OFF/ON states throughout the entire motion for a total of 10 s

6 Conclusions

In this work, we explore a new concept of exercise countermeasure based on modularity that will support crew health and performance during those long-term space missions, i.e., Modular Multi-Motor Exercise System. This innovative concept addresses risks and gaps found within the NASA Human Research Roadmap responsible for understanding and mitigating the highest risks to astronaut health and performance. We focused on developing a system that could maximize the number of different strength training and aerobic exercises that can be performed with a single system while meeting load, volume, and mass requirements for upcoming missions. Our approach combines current exercise countermeasures at ISS with the modular robotics field to create a new type of exercise system that will provide the astronaut with required training.

This approach is based around the unique properties of MR fluid, which has a viscosity that changes according to the strength of the magnetic field applied to it. We presented two prototypes that control magnetic fields in different manners, i.e., Electromagnet-triggered control and Switchable magnet-triggered control. The first prototype has the capability of creating a total of 6 different levels of resistive forces, from a base resistance of 2 lbs to a maximum of 5 lbs, by increasing the voltage levels. Whereas, the second prototype only has two levels of resistive forces, a base of 1.8 lbs and a max of 2.5 lbs, done by turning the switchable magnet OFF/ON. The second main factor that was taken into consideration was power and energy consumption of the device. Due to the nature of the switchable magnet, this prototype requires no energy to provide its resistive force, which is a highly desirable factor when developing space applications. Prototype 1 uses a considerable amount of power, depending on the choice of resistance level. Due to the modular design concept, scalability of forces and configurations is feasible. Resistive forces can be multiplied by the number of modules connected to a single point (e.g. a handle connected to two or three modules to increase force in one direction). Table 6 summarizes model parameters from both triggered-control strategies.

Table 5 Power and energy consumption of EM prototype in relation to its levels

Resistance levels	Voltage (V)	Amperes (A)	Power-consumption (W)	Energy-consumption^a (Wh)
Level 1	0	0	0	0
Level 2	5	0.372	1.86	3.72
Level 3	10	0.746	7.46	14.92
Level 4	15	1.118	16.77	33.54
Level 5	20	1.486	29.72	59.44
Level 6	24	1.844	38.40	88.51

[a] assuming workout time of 2-h

As future challenge, we plan to develop a new module that combines the best features from both prototypes, i.e., the capability to provide different resistive force levels from prototype 1 and the advantage of having a low-power consumption system from prototype 2, while increasing resistive forces up to 50lb per module. To illustrate how this modular system could meet the load range that current devices are able to provide at the ISS, Table 7 displays the number of modules that would be required to

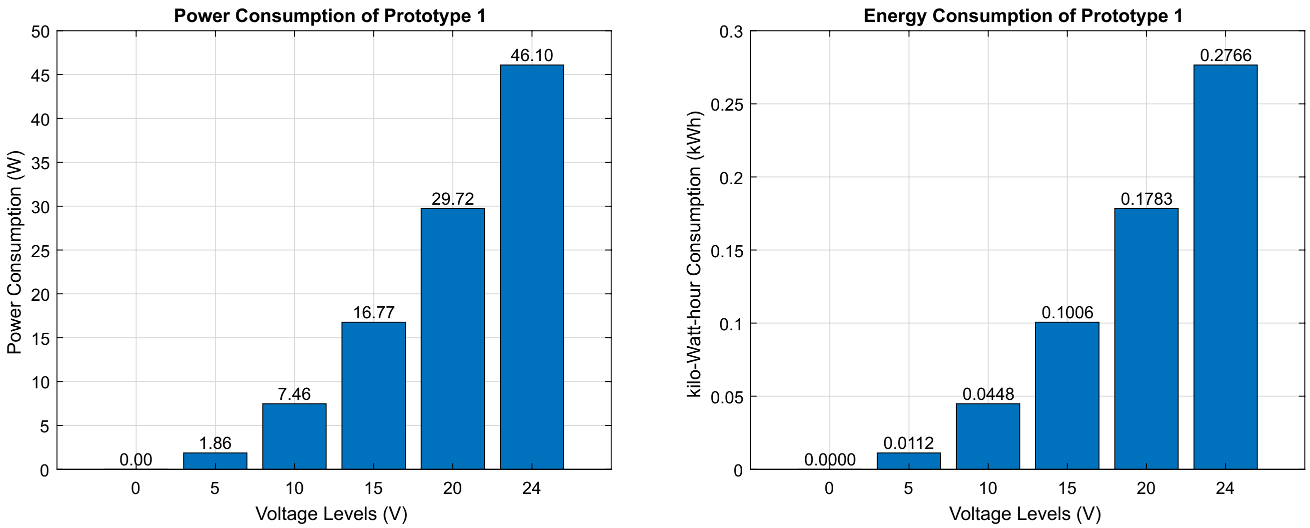


Fig. 9 Power and energy consumption by Prototype 1

provide similar performance. The system, at current state, can be used to provide exercises that provide a load range between 5lb and 150lbs. If each module is able to provide up to 50lbs, then, the number of modules required for each exercise would be drastically reduced, making the system feasible to use for these tasks.

The main benefits that a modular system like this could bring are (1) the possibility of building different configurations that can be used by the astronaut to exercise diverse group of muscles; (2) the possibility to test-validate the efficiency of a wide variety of existing exercise programs or routines; (3) a platform that can be used to evaluate different countermeasures for muscle atrophy, sensory-motor training protocols, in-flight balance assessment and training system, and post-flight rehabilitation strategies; (4) a multi-purpose system that will impact payload criteria and versatility in space missions; and (5) the possibility to transfer the technology for the assessment and exercise of human body movements of stroke survivors and other patients with sensorimotor disorders.

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Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

Table 6 Model Parameters

Prototype	Input	Output (lbs)	Energy consumption (KWh)
Prototype 1: Electromagnet-triggered control	0V	2	0
	5V	2.8	0.0112
	10V	3.5	0.0446
	15V	3	0.1006
	20V	3.5	0.1783
	24V	5	0.2766
Prototype 2: Switchable magnet-triggered control	OFF	1.5	0
	ON	2.5	0.000016

References

1. Baca J, Ambati MS, Dasgupta P, Mukherjee M (2017) A modular robotic system for assessment and exercise of human movement. In: Advances in automation and robotics research in Latin America. Springer, pp 61–70 https://doi.org/10.1007/978-3-319-54377-2_6
2. Baca J, Martinez M (2020) Monitoring human body joint rotations based on wearable magnetic strap modules and the jacobian matrix of magnetic fields. J Eng Sci Med Diagn Ther. https://doi.org/10.1115/1.4046323
3. Baechle TR, Earle RW (eds) (2008) Essentials of strength training and conditioning, 3rd edn. Human Kinetics, Champaign
4. Behbahani SB, Tan X (2017) Design and dynamic modeling of electrorheological fluid-based variable-stiffness fin for robotic fish. Smart Mater Struct 26(8):085014. https://doi.org/10.1088/1361-665x/aa7238
5. Bian H, Chen Z, Wang H, Zhao T (2017) Mechanical design of EFW exo II: a hybrid exoskeleton for elbow–forearm–wrist

Table 7 Exercise—Load range comparison with Modular Multi-Motor Exercise System

Exercise	Load Range	No. of modules required to meet load range	No. of modules required to meet load range w/ modules producing up to 50lbs
Front Shoulder Raise	5–60 lbs	1–12 modules	1–2 modules
Hip Flexion	5–100lbs	1–20 modules	1–2 modules
Bicep Curls	20–150 lbs	4–30 modules	1–3 modules
Bench Press	50–400 lbs	10–80 modules	2–8 modules
Squats	50–600lbs	10–120 modules	2–12 modules

rehabilitation. In: 2017 International conference on rehabilitation robotics (ICORR). IEEE. https://doi.org/10.1109/icorr.2017.8009328

6. Chen F, Cao J, Zhang L, Zhang H, Wang MY, Zhu J, Zhang Y (2017) Networked soft actuators with large deformations. In: 2017 IEEE International conference on robotics and automation (ICRA). IEEE. https://doi.org/10.1109/icra.2017.7989499
7. Chen J, xian Zhang G, Jin J (2007) Preparation and deflection characterization of intelligent polymer gels controlled by magnetic fields. In: 2007 IEEE international conference on robotics and biomimetics (ROBIO). IEEE. https://doi.org/10.1109/robio.2007.4522444
8. Chen Y, Le S, Tan QC, Lau O, Wan F, Song C (2017) A lobster-inspired robotic glove for hand rehabilitation. In: 2017 IEEE international conference on robotics and automation (ICRA). IEEE. https://doi.org/10.1109/icra.2017.7989556
9. Cozens J (1999) Robotic assistance of an active upper limb exercise in neurologically impaired patients. IEEE Trans Rehabil Eng 7(2):254–256. https://doi.org/10.1109/86.769416
10. Duduta M, Clarke DR, Wood RJ (2017) A high speed soft robot based on dielectric elastomer actuators. In: 2017 IEEE international conference on robotics and automation (ICRA). IEEE. https://doi.org/10.1109/icra.2017.7989501
11. Faidley LE, Han Y, Tucker K, Timmons S, Hong W (2010) Axial strain of ferrogels under cyclic magnetic fields. Smart Mater Struct 19(7):075001. https://doi.org/10.1088/0964-1726/19/7/075001
12. Farshad M, Roux ML (2005) Compression properties of magnetostrictive polymer composite gels. Polym Testing 24(2):163–168. https://doi.org/10.1016/j.polymertesting.2004.09.007
13. Gopalakrishnan R, Genc KO, Rice AJ, Lee SMC, Evans HJ, Maender CC, Ilaslan H, Cavanagh PR (2010) Muscle volume, strength, endurance, and exercise loads during 6-month missions in space. Aviat Space Environ Med 81(2):91–104. https://doi.org/10.3357/asem.2583.2010
14. Hesse S, Schulte-Tigges G, Konrad M, Bardeleben A, Werner C (2003) Robot-assisted arm trainer for the passive and active practice of bilateral forearm and wrist movements in hemiparetic subjects 1. Archives of Physical Medicine and Rehabilitation - ARCH PHYS MED REHABIL 84:915–920
15. Koo JH, Dawson A, Jung HJ (2012) Characterization of actuation properties of magnetorheological elastomers with embedded hard magnetic particles. J Intell Mater Syst Struct 23(9):1049–1054. https://doi.org/10.1177/1045389x12439635
16. Marette A, de Saint-Aubin C, Rosset S, Briand D, Shea H (2017) Full integration of a dielectric elastomer actuator with a flexible 1 kV thin-film transistor. In: 2017 19th international conference on solid-state sensors, actuators and microsystems (TRANSDUCERS). IEEE. https://doi.org/10.1109/transducers.2017.7994479
17. Guilliams M, Nieschwitz B, Rapley M, Beyene N (2011) Resistive exercise description document. Preflight and in-flight exercise conditions for astronauts on the international space station. NASA Technical Report. JSC29558
18. McIntyre EC, Yang H, Green PF (2012) Electrorheology of polystyrene filler/polyhedral silsesquioxane suspensions. ACS Appl Mater Interfaces 4(4):2148–2153. https://doi.org/10.1021/am300149u
19. Moore C, Svetlik R, Williams A, (2017) Designing for reliability and robustness in international space station exercise countermeasures systems. In 2017 IEEE aerospace conference. IEEE. https://doi.org/10.1109/aero.2017.7943563
20. Nakamura T, Saga N, Nakazawa M, Kawamura T (2002) Viscous control of a rotating device using smart fluid. In: 7th international conference on control, automation, robotics and vision, ICARCV 2002. Nanyang Technological Univ. https://doi.org/10.1109/icarcv.2002.1234863
21. Pauletto B (1991) Strength training for coaches. Leisure Press. ISBN 9780880113717
22. Rahman MH, Ouimet TK, Saad M, Kenne JP, Archambault PS (2010) Development and control of a wearable robot for rehabilitation of elbow and shoulder joint movements. In: IECON 2010—36th annual conference on IEEE industrial electronics society. IEEE. https://doi.org/10.1109/iecon.2010.5675459
23. Reitelshofer S, Landgraf M, Yoo IS, Horber J, Ramer C, Ziegler C, Franke J (2014) Dielectric elastomer actuators—on the way to new actuation-systems driving future assistive, compliant and safe robots and prostheses. In: 5th IEEE RAS/EMBS international conference on biomedical robotics and biomechatronics. IEEE. https://doi.org/10.1109/biorob.2014.6913877
24. Shan W, Diller S, Tutcuoglu A, Majidi C (2015) Rigidity-tuning conductive elastomer. Smart Mater Struct 24(6):065001. https://doi.org/10.1088/0964-1726/24/6/065001
25. Sibonga JD, Cavanagh PR, Lang TF, LeBlanc AD, Schneider VS, Shackelford LC, Smith SM, Vico L (2007) Adaptation of the skeletal system during long-duration spaceflight. Clin Rev Bone Miner Metab 5(4):249–261. https://doi.org/10.1007/s12018-008-9012-8
26. Smith SM, Heer MA, Shackelford LC, Sibonga JD, Ploutz-Snyder L, Zwart SR (2012) Benefits for bone from resistance exercise and nutrition in long-duration spaceflight: evidence from biochemistry and densitometry. J Bone Miner Res 27(9):1896–1906. https://doi.org/10.1002/jbmr.1647
27. Snyder RL, Nguyen VQ, Ramanujan RV (2010) Design parameters for magneto-elastic soft actuators. Smart Mater Struct 19(5):055017. https://doi.org/10.1088/0964-1726/19/5/055017
28. Stanway R (2004) Smart fluids: current and future developments. Mater Sci Technol 20(8):931–939. https://doi.org/10.1179/026708304225019867
29. Szabó D, Szeghy G, Zrínyi M (1998) Shape transition of magnetic field sensitive polymer gels. Macromolecules 31(19):6541–6548. https://doi.org/10.1021/ma980284w
30. Thompson C, Floyd RT (2011) Manual of structural kinesiology. McGraw-Hill Education, New York (47–53, 115–133)

31. Ubaidillah, Sutrisno J, Purwanto A Mazlan SA (2014) Recent progress on magnetorheological solid: materials, fabrication, testing, and applications. Adv Eng Mater 17(5):563–597. https://doi.org/10.1002/adem.201400258
32. Winter DA (2009) Biomechanics and motor control of human movement. Wiley, New York
33. Xu L, Gu G (2017) Bioinspired venus flytrap: a dielectric elastomer actuated soft gripper. In: 2017 24th international conference on mechatronics and machine vision in practice (M2VIP). IEEE. https://doi.org/10.1109/m2vip.2017.8211523