**Title**
Design and Control of a Series Elastic Resistance Mechanism for Exercise and Rehabilitation

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# Design and Control of a Series Elastic Resistance Mechanism for Exercise and Rehabilitation

A thesis submitted in partial satisfaction of the
requirements for the degree Master of Science in
Mechanical Engineering

by

Kevin Genehyub Gim

2016

## ABSTRACT OF THE THESIS

# Design and Control of a Series Elastic Resistance Mechanism for Exercise and Rehabilitation

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Kevin Genehyub Gim

Master of Science in Mechanical Engineering
University of California, Los Angeles, 2016
Professor Dennis W. Hong, Chair

This thesis proposes a novel mechanism and its control strategy for generating a controllable resistance force for exercise and rehabilitation. Instead of measuring force with a load cell, the idea of a series elastic actuator is applied to perform a feedback force control by calculating force from spring deflection. By introducing series elasticity to an exercise machine, the proposed mechanism is able to achieve the active resistance force control under safe operations and in a cost effective way compared with existing systems. A prototype hardware was manufactured and an impedance control algorithm was developed in order to simulate the effects of a virtual damper, spring and constant force. The hardware design and control algorithm were examined through dynamic simulation and a prototype hardware was used to further verify the ideas.

The thesis of Kevin Genehyub Gim is approved.

Jacob Rosen

Veronica Santos

Dennis W. Hong, Committee Chair

University of California, Los Angeles

2016

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# Acknowledgments

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# Chapter1

# Introduction

Resistance training such as weight lifting has been used in training or rehabilitation to improve strength, physical performance and shape of muscles. The fitness market for exercise apparatuses and accessories has been growing rapidly due to the increased societal focus on health and exercise. Moreover, a need for “smart fitness hardware” has grown with the spread of smartphone applications in the health care industry. Despite this growing demand, exercise equipment used to provide resistance continues to consist of mainly passive mechanisms, such as weight plates or elastic materials.

Barbells and dumbbells are the most common forms of free weights because of their ease of use and reliability. Resistance levels are simply adjusted by adding or subtracting weights. In addition, exercise machines with weight stacks and cable-pulley are also widely used in gyms for convenient and efficient muscle training. These machines utilize cam and link structure to provide a variable exercise load considering the characteristic of muscles. However, resistance training using weights has several limitations. As the resistance increases, it is inevitable that the apparatus will become bulky and heavy. Moreover, passive weights have an inertial effect that causes significant disadvantages to the user. When a weight is being accelerated by a user, the inertial effect can cause the load on the muscle to decrease. This usually abates the effect of the resistance training and may cause injuries to the user due to large load changes on joints and ligament.

In order to overcome the shortcomings of traditional weight training devices, there has been several research and commercial attempts of developing new resistance generating method using springs, pneumatics, hydraulics and/or electric motors. Exercise apparatuses using springs and elastic bands are widely used for rehabilitation purpose or compact training devices. However, since elastic materials are passively stretched to produce the resistance force, the resistance force is dependent on the deformation. This dependency creates a changing force throughout the stroke of the user's exercise, so that the used is hard to identify the resistance levels engaged. The researchers at NASA developed the Interim Resistance Device as a muscle training device for astronauts on the International Space Station. In order to produce resistance in a micro-gravity environment, they introduced 'Flexpack' with a passive elastic element.[2] However, it was considered as a disadvantage that the resistance force changed over the stroke of the exercise due to the passive nature of the device. As a modified space training device, the Advanced

Resistance Exercise Device was developed and is used on the International Space Station currently. This device generates the desired resistance force with vacuum cylinders and simulates the inertial effect of a free weight exercise with fly wheels.[3]

There also have been various research projects to develop an exercise machine by using actuators currently used in the field of robotics. Georgia Tech developed a robotic exercise machine the utilized hydraulic pistons to actively adjust the resistance force.[4] Keiser Inc., developed a commercialized exercise machine that relied on pneumatic pistons to produce the desired force. By introducing controllable pneumatic/hydraulic actuators to produce resistance, smooth resistance profiles can be obtained to reduce shock loading to muscle tissue and joints.[5]

The research on creating an exercise machine actuated by electric motors is also actively being conducted. Roberto Horowitz at UC Berkeley developed a smart exercise machine and its intelligent control strategy. The machine has the form of a 1-dof direct drive robot with a handle. With a DC motor, it simulated a nonlinear dynamic damper which interacts passively with the user to optimize the resistance based on a biomechanic model of the user.[6][7] A haptic control interface for a motorized exercise machine was also researched by Crain R. Carignan. He developed a bicep curl training machine with a force sensor and a linear actuator that implements an admittance control law to generate viscous and inertial resistance.[8] A smart resistance training system was presented at Loughborough University in order to explore the practical application of a motorized exercise machine. The machine is able to provide various exercise modes such as isotonic, isometric, isokinetic eccentric as well as a novel exercise mode termed ‘variokinetic’.[9] A research group at Korea University also developed a haptic-based resistance training machine. Different from previous approaches, the machine introduced two AC servo motors and a 6-axis Force/Torque sensor to generate arbitrary two-dimensional motion and resistance using an impedance control scheme.[10][11]

Although there have been numerous research projects in this field, there are only a few machines that have advanced to practical products. Most of the described machines measure force with a Force/Torque sensor on a rigid linkage system. This apparatus leads to high manufacturing cost as well as the possibility of injury or damage in the case of a malfunctioning unit. Therefore, this research is focused on developing a novel exercise machine that provides a controllable resistance force but also can be advanced to a practical product with safe operability and low manufacturing price.

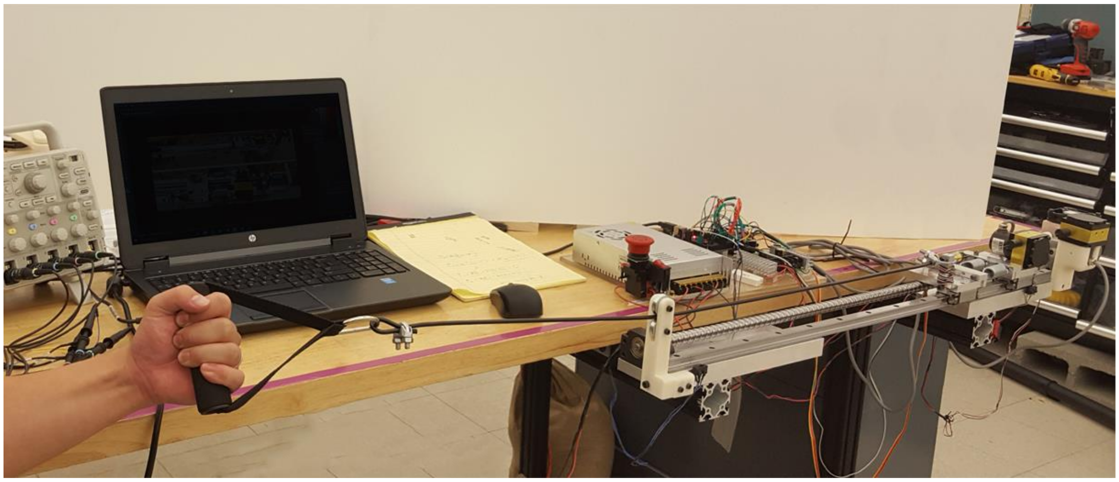

Figure 1. An example of exercising with the prototype

Therefore, this research purposes a novel series elastic resistance mechanism for exercise and rehabilitation. An example of exercising with the prototype is shown in figure 1. Different from the previously mentioned research machines this series elastic resistance mechanism measures the force based off of the elongation of the linear springs. The current mechanism is designed in the form of a cable resistance machine. The series elastic element replaces the weight stacks in a conventional cable resistance exercise machines.

This mechanism resembles a “Series Elastic Actuator” (SEA). Series elastic actuators are used in humanoid robots and prosthetic devices to achieve stable force control. By applying a SEA to generate resistance force, the mechanism has the following benefits:

1. Programmable resistance force.
2. Protects a user from large impulses or possible malfunctions.

3. Low manufacturing cost compared with the existing powered exercise devices.
4. Compact and lightweight hardware
5. Provides a user-interface for smart fitness applications.

First, since the mechanism is capable of directly measuring the resistance force, it can perform feedback control on the resistance force. Therefore, the mechanism can generate arbitrary desired resistances with various resistance strategies. Not only can the mechanism provide a constant resistance force for isotonic training, the mechanism can also provide virtual mass, damper, and spring forces by implementing impedance control. Damping or elastic resistances are widely used in trainings for rehabilitation of injured or elderly people.[12] Therefore, by simulating the effect of a damper and spring, the mechanism is able to be utilized as a rehabilitation device as well as a weightlifting machine. Moreover, since the resistance force is programmable, it is possible to develop more efficient resistance strategies according to bodybuilding strategies or considering a neuromuscular characteristics of humans.

Second, by introducing compliant linear springs instead of a stiff load cell, it filters out noises and protects the user and the machine from large impulses. Safe operation is considered as the most important factor for human-robot interactive mechanisms. Moreover, the movement of users is highly unpredictable which can cause impulsive input or sudden release. In these circumstances, systems with rigid links and a stiff load cell have a greater probability of hurting the user because of rapid movements or malfunctioning sensors. However, the compliance of the springs protects the user and the hardware from the impulsive input or output. In addition, by using a cable to transmit resistance force, the mechanism cannot hit or push the user but can only can drag which also reduce the probability of an accident.

Third, since the mechanism uses linear extension springs instead of a load cell, the manufacturing price is significantly reduced. When a load cell is used for a force feedback, usually a high speed amplifier and processor is required in order to get a high sample rate which causes an increase in the manufacturing cost. However, by replacing a load cell with linear springs, both the cost is as well as required specification of processing power are reduced.

By generating the force with an electric motor, the size and overall weight of the hardware is significantly reduced comparing with existing applications. Unlike weight stacks, the size and weight of the mechanism doesn't have to be increased as the resistance force increases. It can be also applied to an exercise device in a microgravity environment because it doesn't produce the resistance force with the gravity.

Finally, since the resistance mechanism is motorized system, it can provide a user-interface which can collaborate with a smart fitness application. Although smartphone applications are widely used in sports for various purposes, there are few resistance training machines that can communicate with smartphones. Therefore, most "smart fitness" applications for muscle trainings requires the user to log their exercises. The series elastic resistance mechanism can connect to a smartphone in order to allow the user to set the resistance levels and automatically logs exercises. This provides the user with a more efficient and convenient workout experience.

In this paper, the concept and benefits this weight training machine are presented in the following order: the benefits of a series elastic resistance mechanism in Chapter 2. The mechanical design of a prototype is demonstrated in Chapter 3. In Chapter 4, the dynamic model of the system and an impedance control scheme are described. Dynamic simulation using MSC Adams and MATLAB/Simulink is conducted in order to validate the design of the prototype and to compare the constant resistance from the mechanism with the resistance from conventional weight stacks. The simulation results are presented in Chapter 5. Experiment results of impedance control with the prototype hardware are given in Chapter 6. Conclusions and future research plan are presented in Chapter 7.

# Chapter 2

# Series Elastic Actuator

In this chapter, the concept of series elastic actuators and their benefits are summarized to explain the application of a series elastic actuator to control resistance for exercise and rehabilitation. There are several ways to achieve force control in robotic systems. Jerry Pratt summarized the characteristics of the traditional force control technologies in: Direct drive current control, pneumatic & hydraulic force control, and force feedback control using a load cell. [13]

The traditional force control method measures torque based on the motor current. This technique shows good force control performance in a direct drive or low gear ratio actuator. However, for robotic applications motors usually require low speed-high torque outputs. Therefore, motors either need to be very high powered or have a large gear ratio. A large gear reduction requires a large force to back drive the motor. Therefore, it is impossible to perform force control with only measuring the current used in the motor.

Pneumatic and hydraulic force control is achieved by measuring pressure instead of electrical current. However, both cases have difficulty controlling small force due to the seal friction of the piston. Jerry Pratt also addressed the limitations of both systems; low power density and difficult position controllability of pneumatic system and high impedance of hydraulic system.

Therefore, a number of force controlled systems use a force sensor (load cell) to measure the torque at the actuator. Because of the active force sensing with closed loop control algorithm, a higher fidelity force control is attainted by reducing the effects of friction, inertia. However, the load cell method has several drawbacks. Since the load cell is very stiff and rigid, it is difficult to have high control loop gains which makes the system slow and unable to respond to small forces. In addition, shock and impulsive inputs/outputs can easily damage the actuator and the environment because of the rigidity of the system. In addition, force control achieved with a load cell usually requires a high sample rate which increase the processor capability requirement.

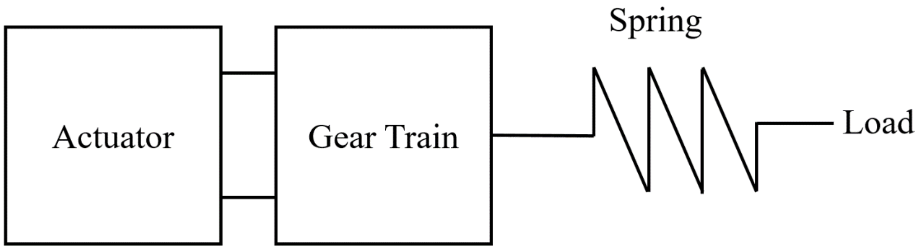

Figure 2. Schematic diagram of Series Elastic Actuator

Therefore, Gill Pratt purposed the configuration named a “Series Elastic Actuator” that reduces interface stiffness by placing an elastic element between the actuator and the end-effector in series.[14] He concluded that by reducing the stiffness of the system, there are a number of benefits for the force control applications. The compliant spring between the load and the actuator acts as a low-pass filter that filters shock loads. As a trade-off it also filters out impulsive outputs of the actuator, which can be rather advantageous for human-robot interaction system for safety reasons. The series elasticity also improves stability and accuracy of force control at low frequencies by lowering the interface resonances.

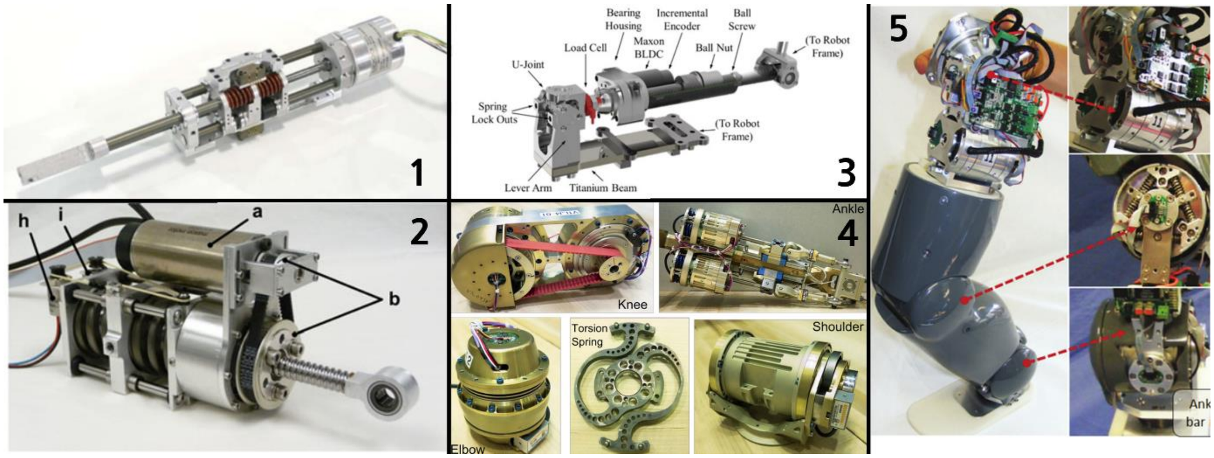

Figure 3. Various series elastic actuators: 1) Linear SEA developed by Jerry Pratt, 2) UT-SEA[15], 3) THOR linear SEA, 4) SEA of the humanoids NASA-JSC Valkyrie, 5) SEA of the humanoids COMAN

Due to these benefits, there has been a lot of series elastic actuators used in the field of robotics, especially for applications that interact with humans and environment such as exoskeleton[16][17], rehabilitation robots,[18] humanoids[19]–[21], and prosthetic devices[22]. Since a resistance training device also requires controlled resistance forces while interacting with a user, applying series elasticity to the machine provides many benefits.

# Chapter 3

# Prototype Design

The prototype is designed in the form of a cable exercise machine. The series elastic mechanism is used to replace the weight stacks in a conventional Cable-Pulley weight training machine.

Figure 4. Conventional Cable-Pulley weight training machine and its weight stacks

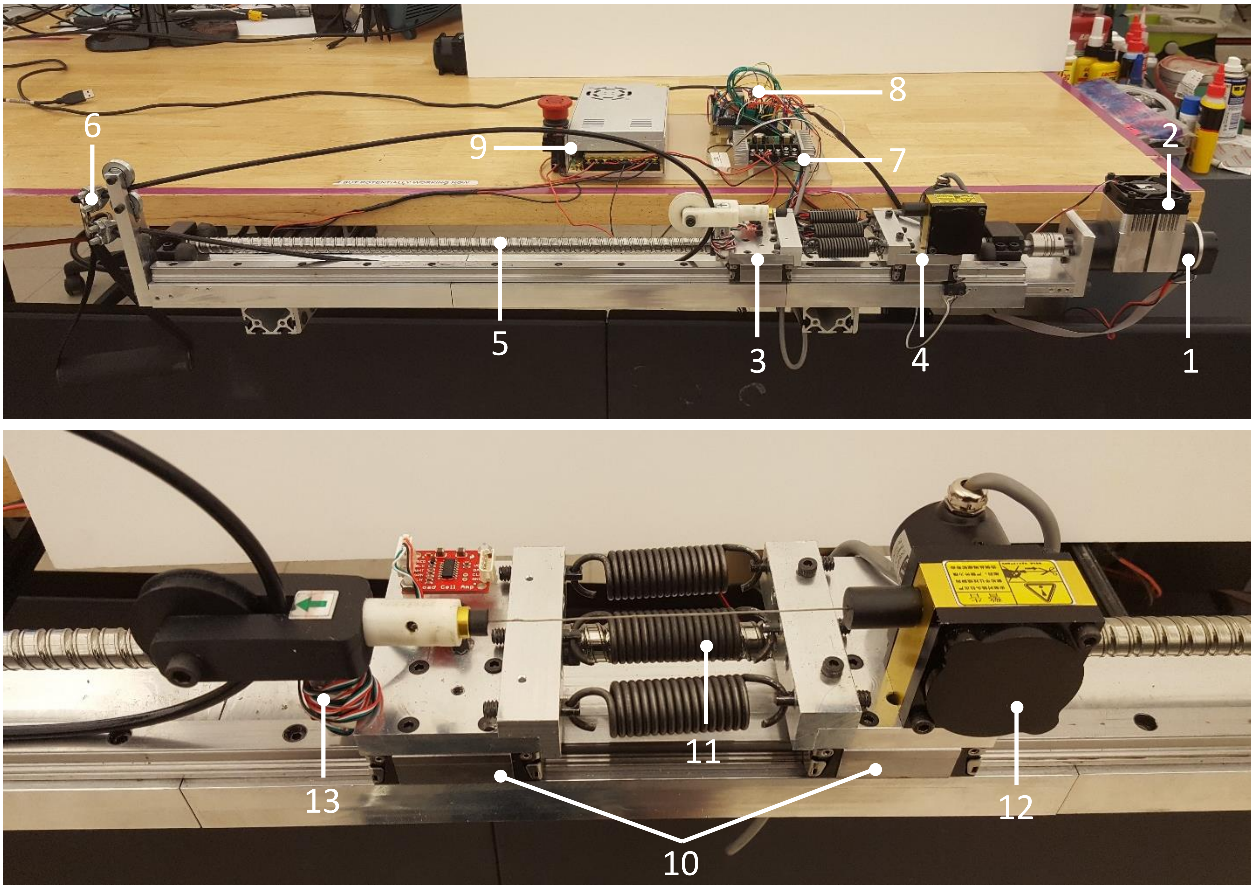

Figure 5. Overall view of the prototype hardware (top), moving parts of the prototype hardware (bottom)

The prototype is shown in Figure 4. The prototype is composed of the following parts: 1) A DC motor with an optical encoder, 2) A motor heat sink, 3) Cart1 dragged by a cable 4) Cart 2 with a ball screw nut driven by a ball screw, 5) A ball screw coupled to the DC motor, 6) A handle and a cable, 7) A DC motor driver, 8) A Micro Controller Unit, 9) A power supply, 10) A linear guide rail and bearing carriages, 11) Linear extension springs connect Part 1 and Part 2, 12) A wire draw encoder, 13) A load cell.

There are two main carts, one is a passive cart and the other one is an actuated cart. Cart 1 is a passive cart that is connected to the cable and handle that a user drags to perform exercises. Cart 2 is driven by the ball screw. The linear extension springs couple the two carts, so that by measuring the deformation of the springs, it is possible to calculate the force exerted on the user.

A 200W Maxon RE 50 DC motor was used in order to perform the force control. The prototype is designed for mainly arm exercises of an average adult who can produce between 50 to 150W during arm exercises[23]. To convert the DC motor's rotary motion to linear motion the following gear reduction formula was used:

$$\frac{F}{\tau} = \frac{2\pi\eta}{l} \qquad (1)$$

Where $l$ is the pitch of the ball screw which is 10mm and $\eta$ is the efficiency of the ball screw which is normally considered to 90%. Using the motor's nominal torque, the thrust force was found to be 229N at the most efficient point. Also the maximum trust force can be generated with the stall torque is up to 5044N. Considering the capability of humans and the maximum capable weight of existing exercise machine, the maximum resistance force of the prototype is limited to 294N which is equivalent with the weight of

30kg mass.

The prototype is designed to have linear movement by using the ball screw and the linear guide. The overall length of the ball screw is $800mm$. A set of movable pulley and fixed pulley are applied to increase the maximum exercise stroke. Therefore, the capable exercise stroke has $1500m$ length, which can cover most of the arm training movement. By applying the pulley mechanism, the effect of inertia of moving parts on actual exercise resistance is also reduced.

Linear extension springs are used as the series elastic element for the system. The linear extension springs allow for simple force measurements by multiply the deformation of the springs and their spring constant by the Hooke's law. In addition, the springs act like a low pass filter and shock absorber which protects the user and the machine from large impulses. With linear springs, it is easy to adjust the spring coefficient by connecting multiple springs in parallel. This allows for the mechanical stiffness of the series elastic resistance mechanism to be optimized for a given exercise.

In order to generate the maximum resistance force within the elastic deformation range of spring, multiple springs are used in parallel. It is decided to use three linear extension springs with the rated spring constant of $38.30lbs/in\,(6.7N/mm)$ which has maximum load of $50lbs$. An actual spring constant of the springs were measured by an experiment. Figure 6 shows the experiment result of testing the stiffness of springs.

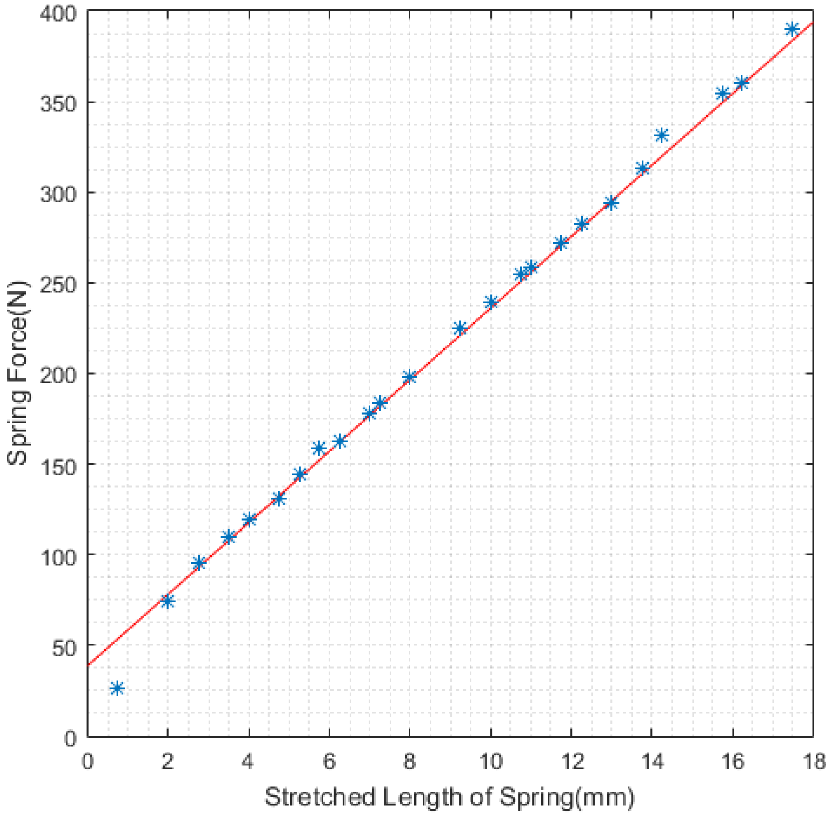

Figure 6. Experiment result of the sping constant measurement

The expected value of the spring constant was $20.9N/mm$. From 31 samples, the sprig equation was found to be $F = 19.71x + 38.82$ . As a result, the actual spring constant is $19.71N/mm$ which is close to the expected value calculated from the rated spring constant. However, the spring shows non-linear behavior at small deformations.

Two encoders were utilized to measure deformation of the springs and rotation of the motor respectively. The wire encoder which is composed of a rotary optical encoder and a self-winding wire as a tape measure is applied to measure the deformation of the springs. Various range sensors were tried to measure the distance between the two carts. However, the wire encoder was found to be the most appropriate sensor for this application due to its characteristics of high resolutions, absence of noise, fast response speed, and high sample rate. The wire encoder in the prototype has $80\mu M / cyc$ resolution and a $1.5m$ maximum wire pull length. The other rotary incremental encoder measures the rotation of the motor which has a resolution of $20\mu m / cyc$ for a linear travel of the ball screw nut. There is also a 3-axis accelerometer to sense the acceleration of Cart 1.

The prototype hardware is controlled by an Arduino MEGA as the Micro Controller Unit which has a $16MHz$ clock speed. In addition, Bluetooth communication is used to connect the Arduino board with an Android smartphone. This allows the user to set resistance input command and monitor the sensor readings through a user-interface made with an Android application.

The PWM DC motor speed control driver is applied to control the velocity of the motor. The motor is treated as a velocity source rather than a torque source. The idea to control a series elastic actuator with a velocity control driver to perform force control is suggest by Robinson in [24]. Velocity control of a DC motor is straightforward and can be easily achieved compared to that of current control of a motor.[25] In addition, velocity based control is considered to be more appropriate for the application because the control objective of the series elastic resistance mechanism is to control the stretched length of the springs. Since one cart will be moving due to user inputs the other cart will have to match the input velocity in order to provide the necessary stretch length of the springs between the two carts. In addition, PWM DC motor drivers generally have a lower price than that of a current control driver.

# Chapter 4

# Controller Design

The series elastic resistance mechanism can be represented as a spring coupled 2-DOF system.

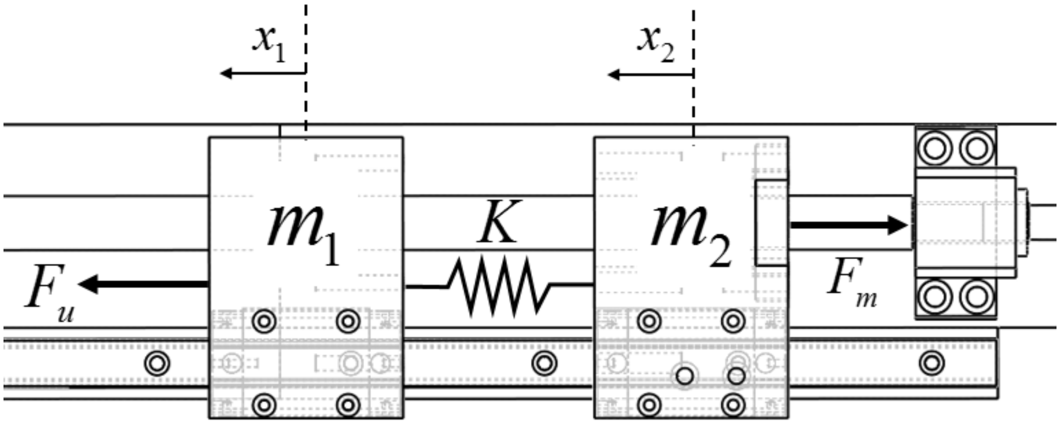

Figure 7. Schematic illustration of the series elastic resistance mechanism

Figure 7 demonstrates a schematic illustration of the series elastic resistance mechanism. $m_1$ is the mass of Cart 1, that is dragged by a cable with a user force, $F_u$. $x_1$ is the displacement of the Cart 1 cause by the user's exercise movement. $m_2$ is the mass of Cart 2 driven by the rotation of the motor which causes the linear displacement $x_2$.

The two carts are coupled with the set of linear extension springs with a spring constant $K$. By measuring the stretched length of the spring, which is equivalent to the changed distance between the two carts, the spring force $F_s$ is calculated as $K\left(x_1 - x_2\right)$ by the Hooke's law. There are fiction force $F_{f1}$ and $F_{f2}$ on the movement of the each carts respectively. Dynamics of the exercise system are of the following form:

$$m_1\ddot{x}_1 + \sigma_{f1}\dot{x} + K(x_1 - x_2) = F_u \tag{2}$$

$$m_2\ddot{x}_2 + \sigma_{f2}\dot{x}_2 + K(x_2 - x_1) = F_m \tag{3}$$

Eqn.(2) denotes that the user force $F_u$ is composed of the force resulting from the accelerate of $m_1$, the spring force $F_s$, and the friction force $\sigma_{f1}\dot{x}$. The spring force and the friction force act as resistance force when the user drags the cable. In other words, the resistance force can be controlled as a desired value by controlling the deformation of the spring if the friction force is compensated for.

The fiction compensation has been an important issue in actuation. Although there has been active research involving friction models, it is difficult to establish an exact model for the friction phenomena. [25] Among many fiction models, a viscous friction force model is used to model the friction force which is linear with respect to the velocity.

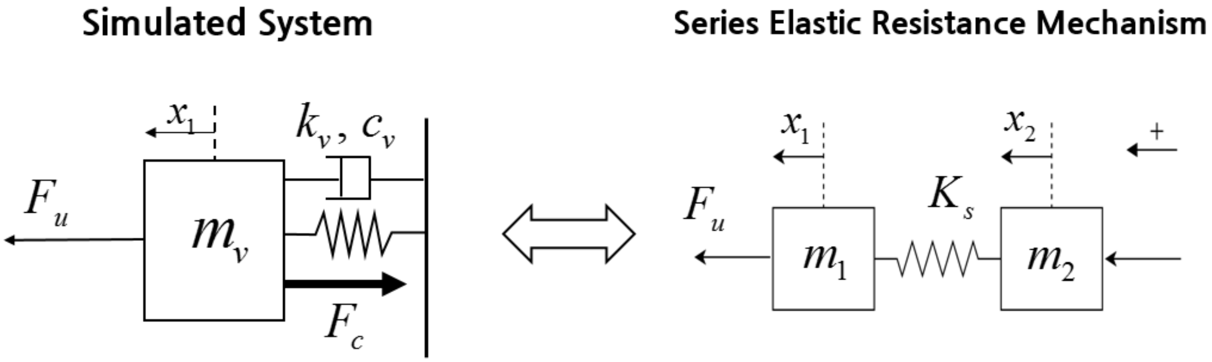

Figure 8. Schematic diagram of a target system and a series elastic mechanism

Figure 8 shows a target system on the left that is simulated with the series elastic resistance mechanism on the right. The simulated system provides a constant resistance for isotonic exercises, but also a virtual mass, damper, and spring by implementing impedance control. The desired user force, $F_d$ can be set up as follows:

$$F_d = m_v \ddot{x}_1 + c_v \dot{x}_1 + k_v x_1 + F_c = K_s(x_1 - x_2) \tag{4}$$

Where $m_v$, $c_v$, and $k_v$ is a virtual mass, damping, and stiffness to be simulated and $F_c$ is an arbitrary force. In conclusion, while the user moves the handle to $x_1$, the motor generates the desired resistance force by manipulating the displacement of Cart 2 ($x_2$) to control the extended length of the springs.

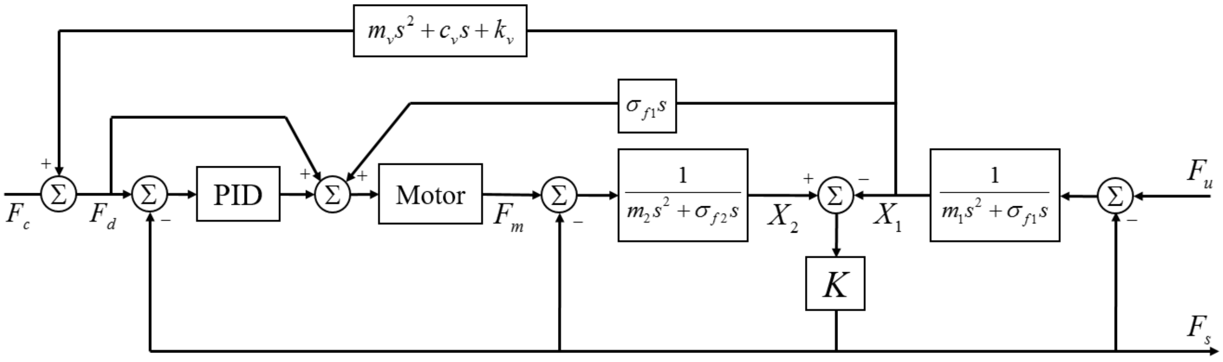

Figure 9 Control algorithm of the series elastic resistance mechanism

Figure 9 shows the block diagram of the proposed resistance force control. A PID controller is implemented to eliminate the error between $F_d$ and $F_s$. $F_d$ is fed forward to the motor input in order to compensate for the effects of $F_s$ on Cart 2. A feedback fiction compensation is implemented by feeding back the of velocity of Cart 1 with a proportional gain. The position, velocity, and acceleration of Cart 1 is also used to simulate effects of a virtual mass, damper, and spring system. Although most control schemes for controlling a series elastic actuator use a PD controller, an I gain was introduced in this application for increased accuracy of tracking a desired force. In order to avoid accumulation of error, due to the I gain, when a new input command is given, the error is zeroed whenever a new desired input is set.

# Chapter 5

# Dynamic Simulation Result

Dynamic simulations using a co-simulation of MSC Adams and MATLAB/Simulink were conducted to validate the mechanical design and control algorithms. In addition, a simulation was conducted to compare the conventional system using weight stacks with the purposed novel mechanism.

A virtual prototype is established with MSC Adams by importing a CAD model of the prototype and defining mechanical components in the simulation. A controller is realized with MATLAB/Simulink. The torque of the DC motor is modeled using a voltage-velocity equation of a DC motor.

$$\tau_{motor} = \frac{K_T}{R}\left(V - K_E \omega\right) \tag{5}$$

Where $K_T$ is the torque constant, $K_E$ is the back emf constant, $R$ is the resistance of the motor, and $\omega$ is the speed of motor. The value of $K_T$, $K_E$, and $R$ are $38.5mNm/A$, $248RPM/V$, and $0.103\Omega$ respectively according to the manufacturer's datasheet. The input voltage is imported from the controller in MATLAB/Simulink. The simulation was able to verify the design and the control logic as well as test the mechanism in extreme conditions to determine the performance limits.

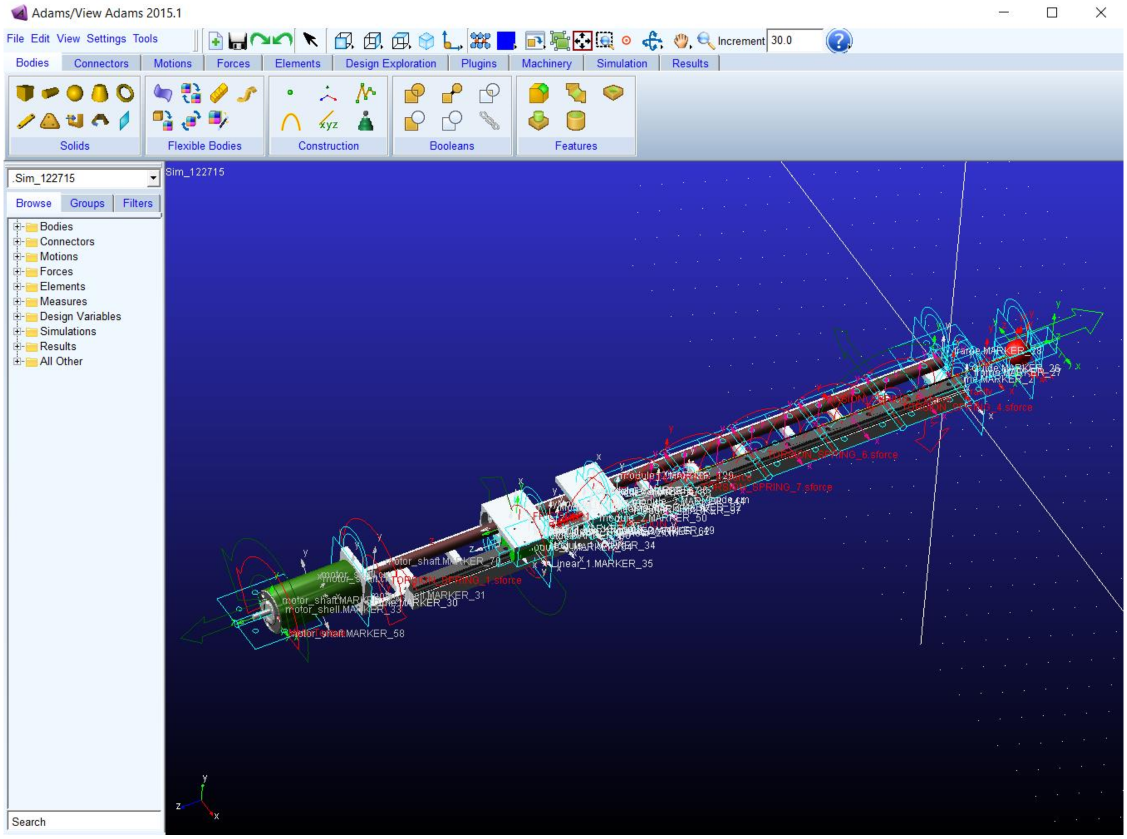

Figure 10. Dynamic Simulation Model of the prototype in MSC Adams

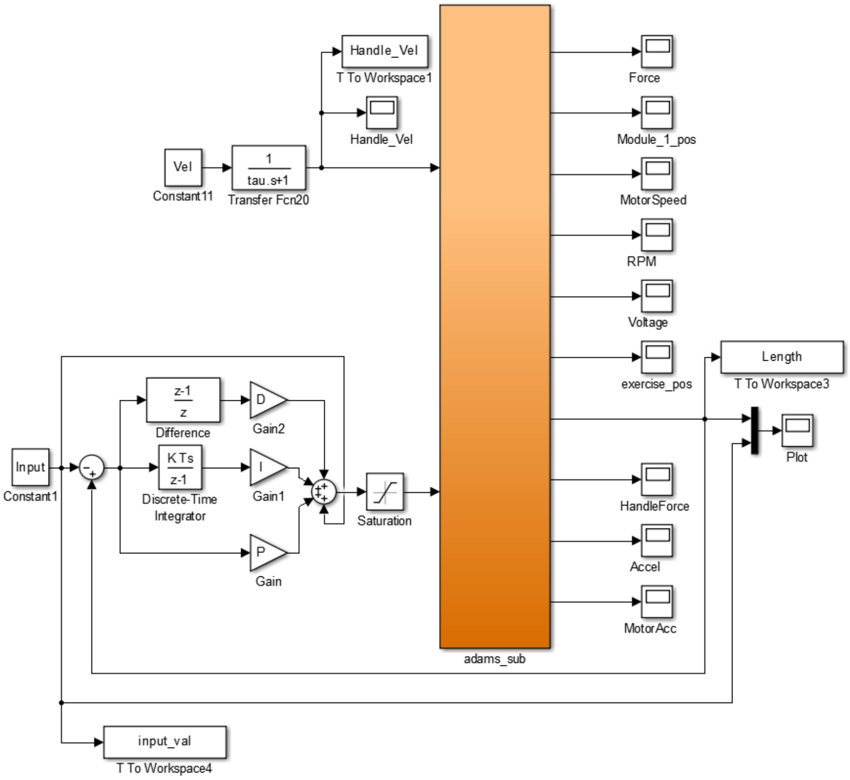

Figure 11. A PID controller of the prototype in MATLAB/Simulink

The controller made with MATLAB/Simulink is shown in Figure 11. For the simulation, only a constant resistance force is used as a desired input. In co-simulation of MATLAB/Simulink and MSC Adams, the two software programs communicate with each other in order to export and import variables. The deformation of the spring occurs in the dynamic simulation model which is exported to the controller in MATLAB/Simulink. The MATLAB/Simulink controller uses this deformation to calculate the motor voltage which is sent to the motor equation of the simulation model to generate the motor torque.

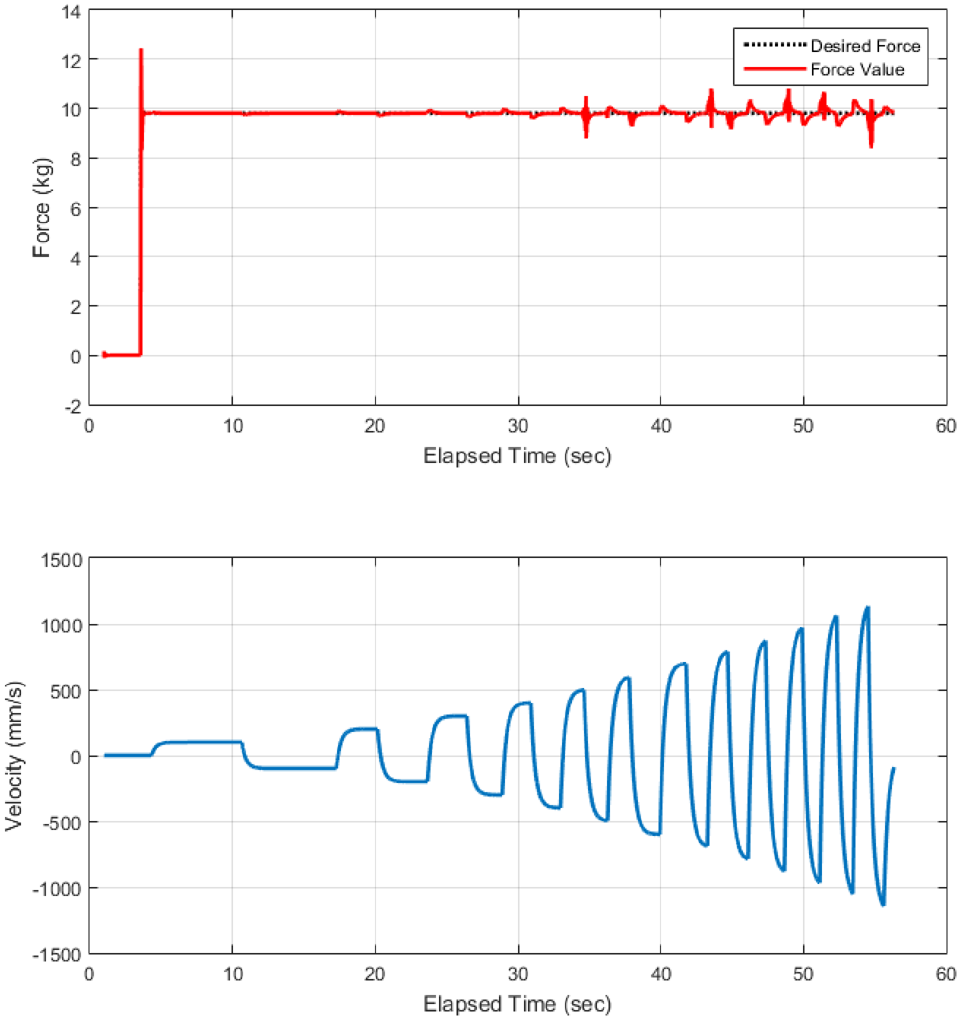

Figure 12. Dynamic simulation result of the prototype with 10kg resistance force input

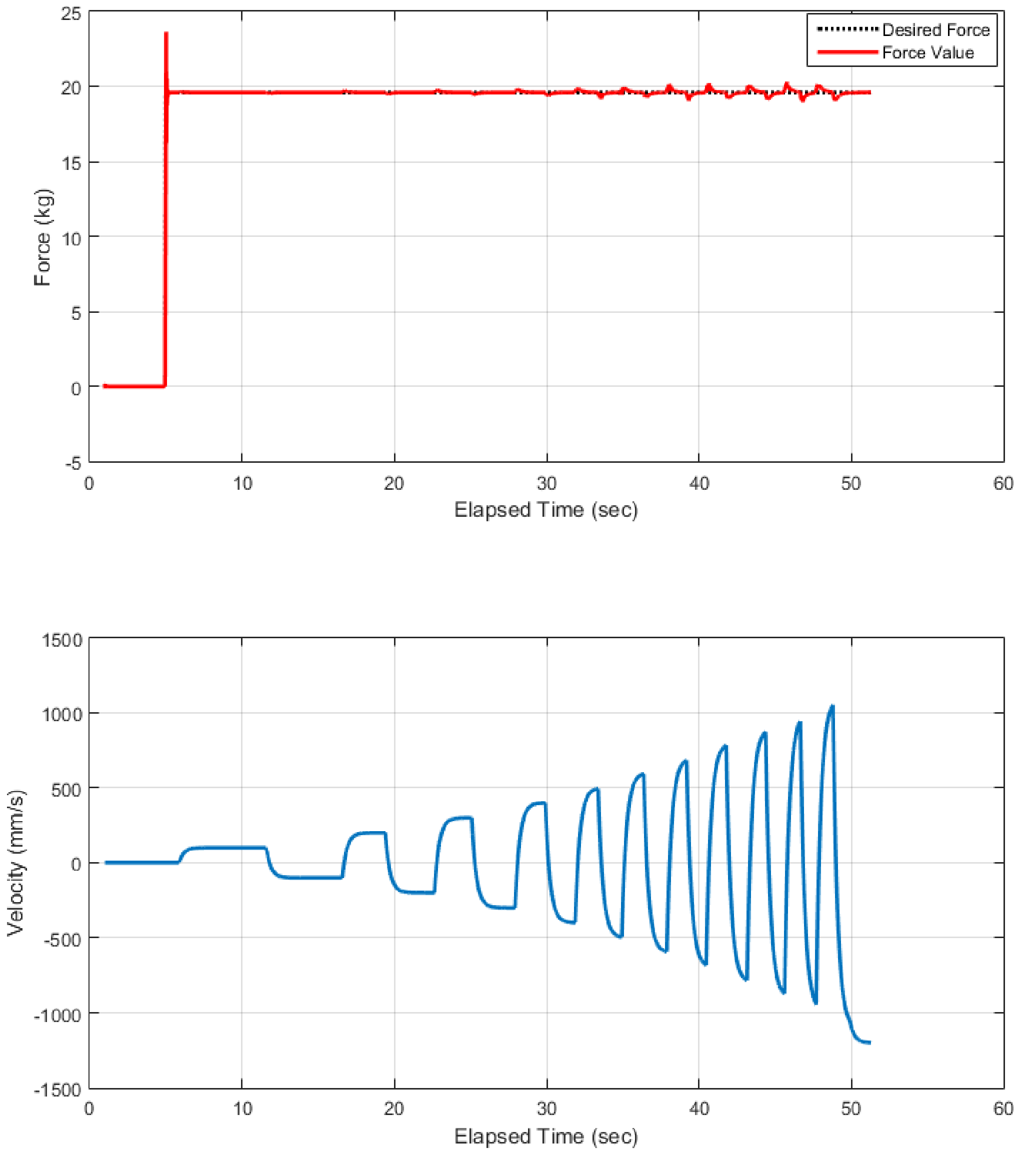

Figure 13. Dynamic simulation result of the prototype with 20kg resistance force input

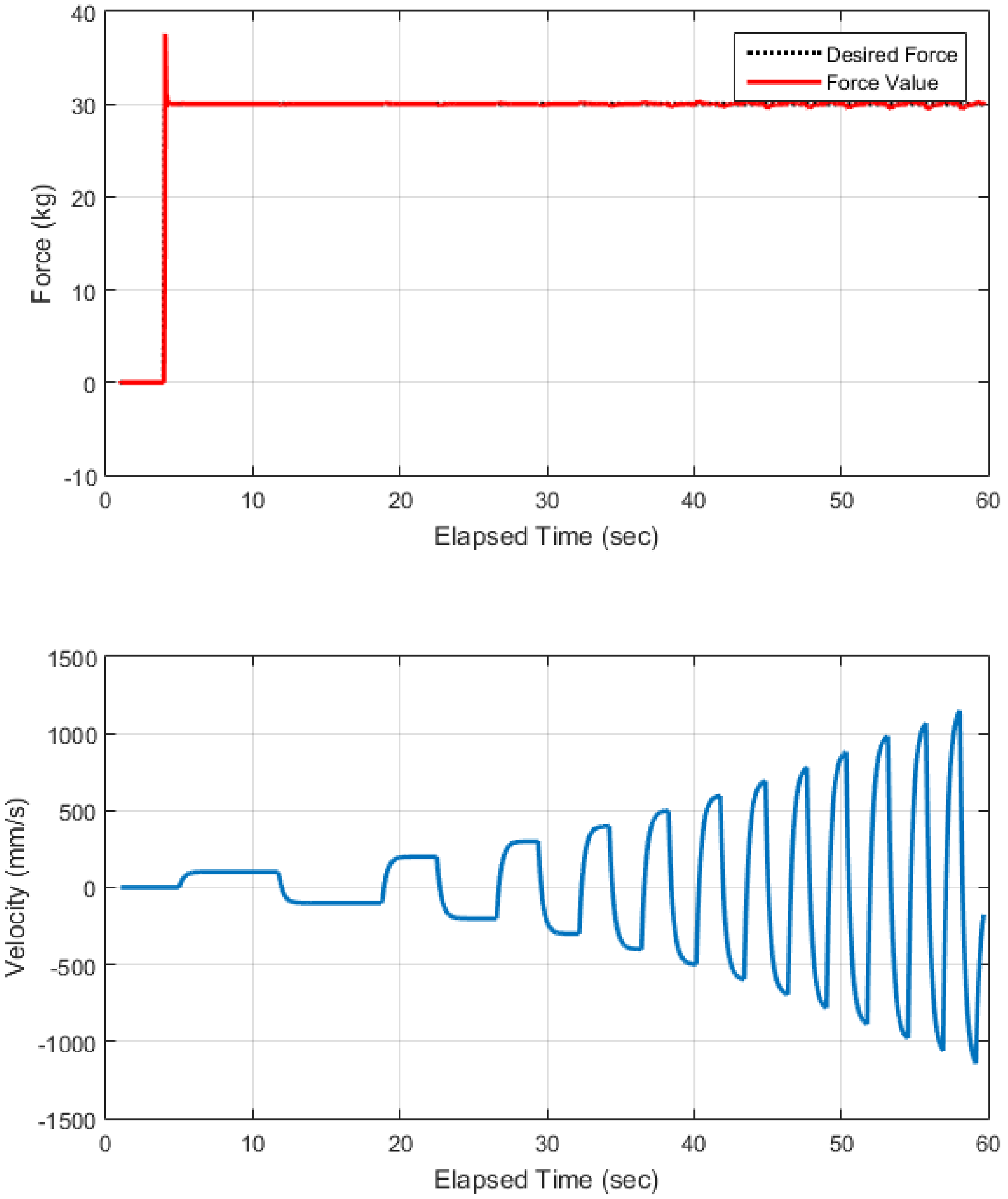

Figure 14. Dynamic simulation result of the prototype with 30kg resistance force input

Figure 12, 13, and 14 shows the results of simulating a desired input of 10kg, 20kg, and 30kg respectively. The second graph in each figure shows the velocity of the input handle. The first stroke uses a constant velocity of $100mm/s$. Each stroke after increased in velocity by $100mm/s$ up until $1200m/s$. The simulation results show that the measured spring force was able to track the input value with errors less than 1kg. This was even true for a stroke with a velocity of $1200m/s$ speed, which can be considered as an extreme condition that is outside the range of human capability.

To compare the prototype to a conventional exercise device with weight stacks a dynamic simulation of a conventional exercise machine was also performed. The conventional exercise device was modeled as a cable-pulley system with weights of 10kg, 20kg, and 30kg that were connected to a movable pulley for each cases. The same exercise motion was used for this simulation. Figure 15, 16, and 17 shows the simulation results.

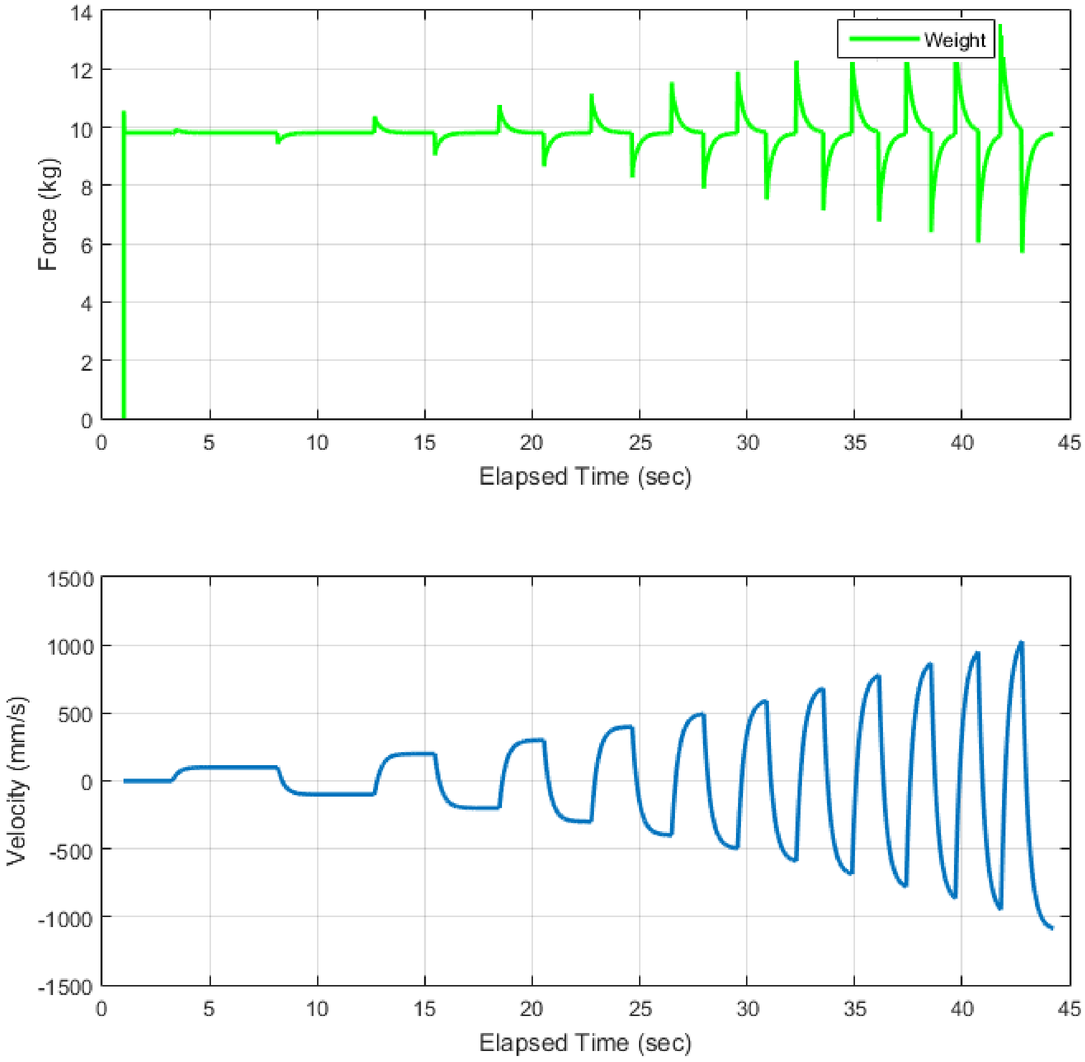

Figure 15. Dynamic simulation result with a 10kg weight

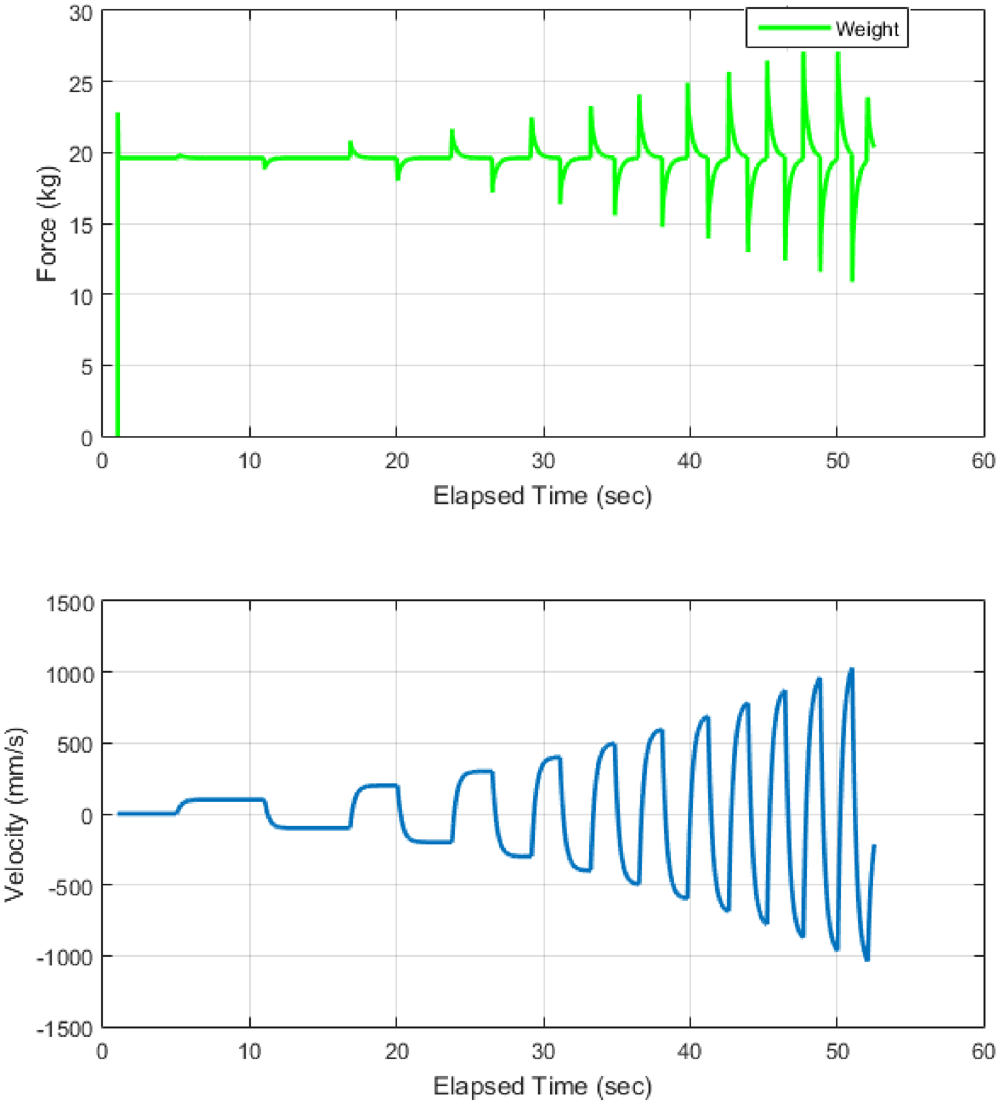

Figure 16. Dynamic simulation result with a 20kg weight

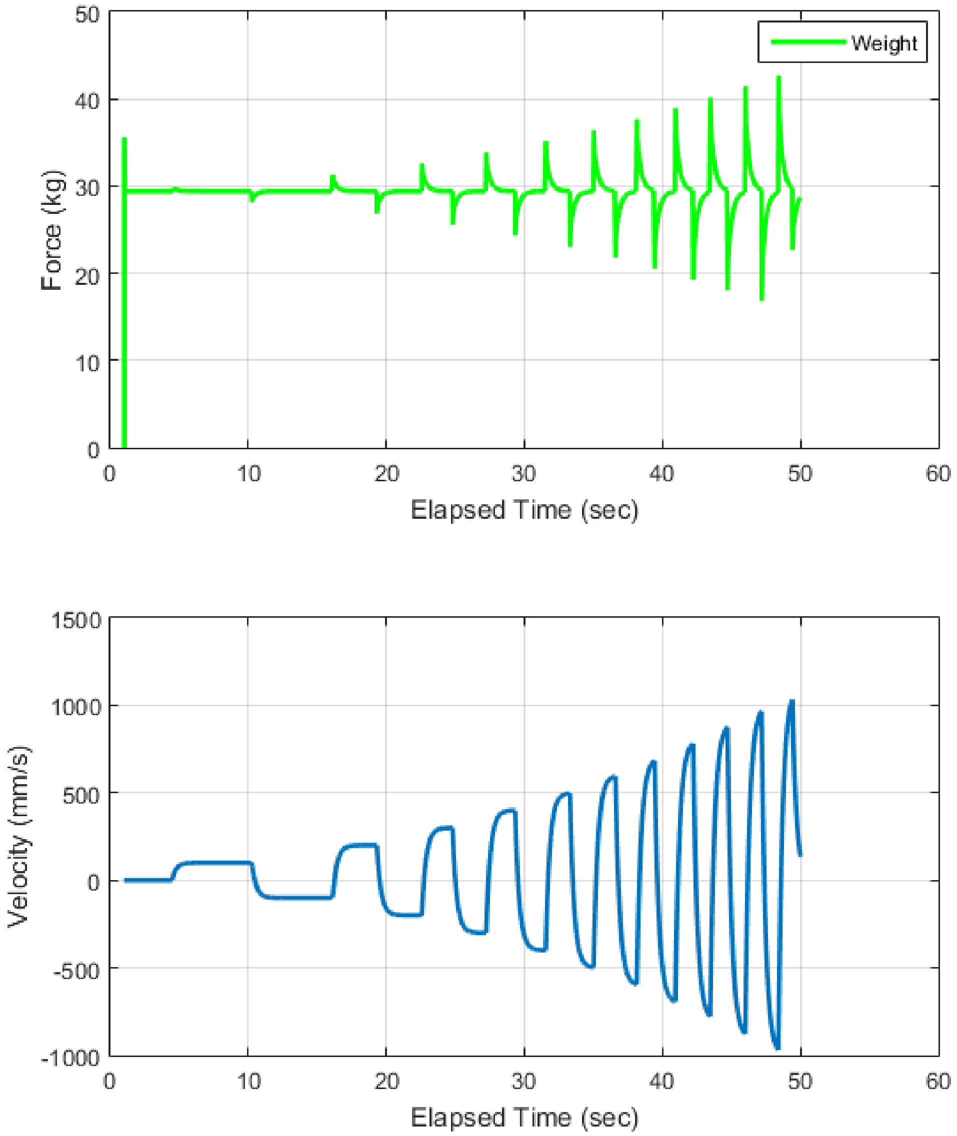

Figure 17. Dynamic simulation of result with a 30kg weight

As expected, an inertial effect on the mass creates a fluctuation of the resistance force. In particular, the sharp increase/decrease in force that appears when changing the direction can not only reduce the effect of the exercise, but cause injuries. Therefore, it is concluded that the resistance load from weights is not optimal for exercise and rehabilitation because of the influence of acceleration which cause uneven force and heavy loads on joint and ligaments.

# Chapter 6

# Prototype Hardware Experiment Result

Two sets of experiments were conducted to validate the operation and the control strategy of the prototype hardware. The objective of the first experiment was to show the force control capability of the prototype by tracking a constant desired force. Analogous to that of the dynamics simulation experiments, experiments were conducted with 10kg, 20kg, and 30kg resistance force input. The tensile force of the cable is measured with a load cell to compare the actual resistance force exerted to the user with the spring force.

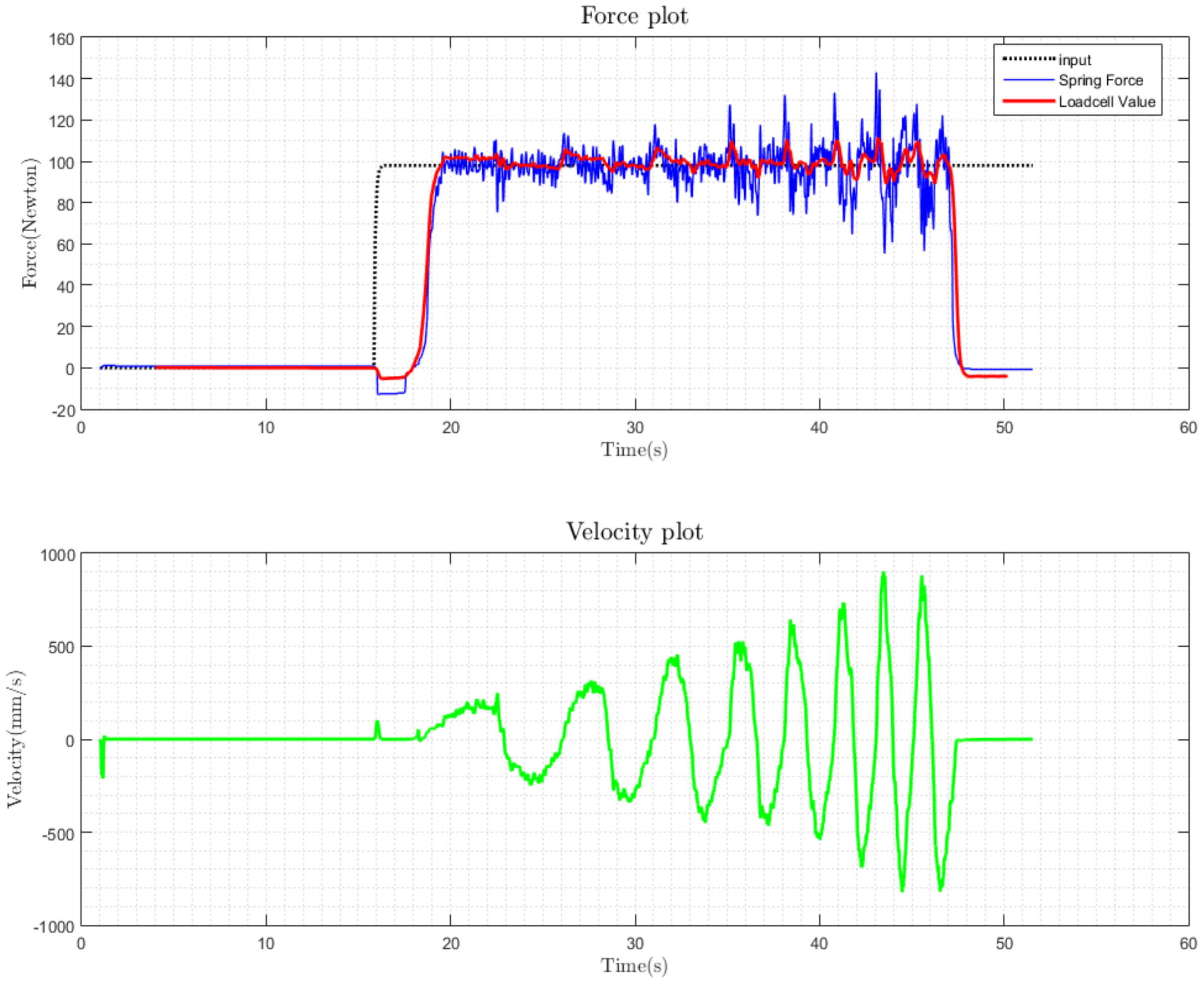

Figure 18. Experiment result of the prototype hardware with a 10kg input resistance force

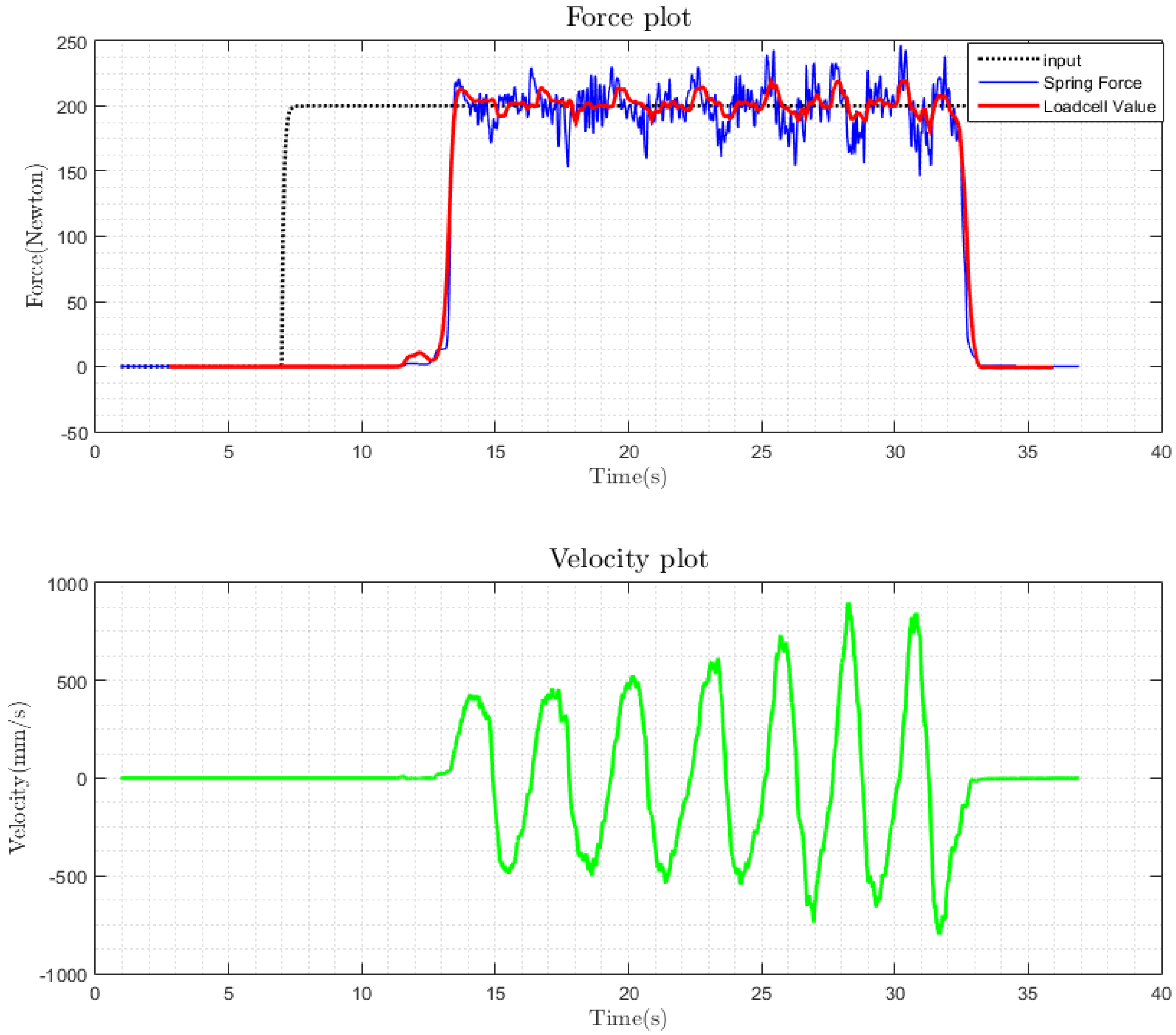

Figure 19. Experiment result of the prototype hardware with a 20kg input resistance force

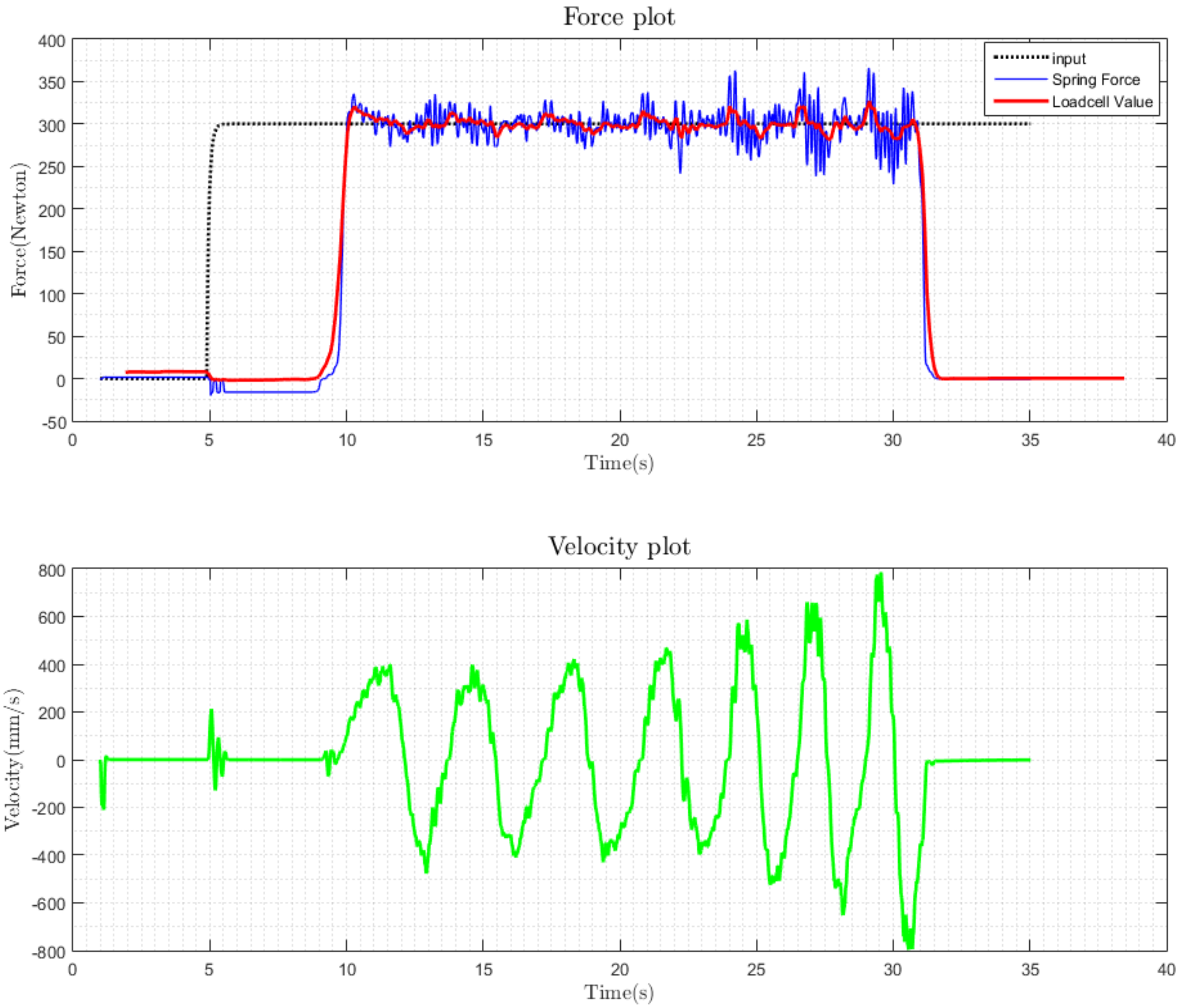

Figure 20. Experiment result of the prototype hardware with a 30kg input resistance force

As shown above, it is clear that the mechanism is able to track the desired input. The measure value of tensile force of the cable by the load cell also shows that a desired resistance force was provided to the user. As the exercise velocity got faster, the error increased especially then the direction of the movement was reversed. The maximum error of $27N$ occurred under the velocity of $786.3m/s$ with the $30kg$ input. For better error rejection performance, it is required to compensate the influence of acceleration when the direction is changed. The friction model with viscous damping also deteriorate the accurate force control since the friction force was not perfectly compensated. In addition, there are some noise because of the low sample rate of the control algorithm. Also an oscillation of the base where the prototype was installed is another reason of the undesirable noise.

The second set of experiments were conducted to validate the impedance control algorithm of the prototype. Pure damping with a constant force impedance was examined with the force model of $F_d = -100\dot{x}_1 - 98$. Figure 21 shows the result of the experiment. As the exercise velocity changes, the control input is also dynamically adjusted depending to the velocity.

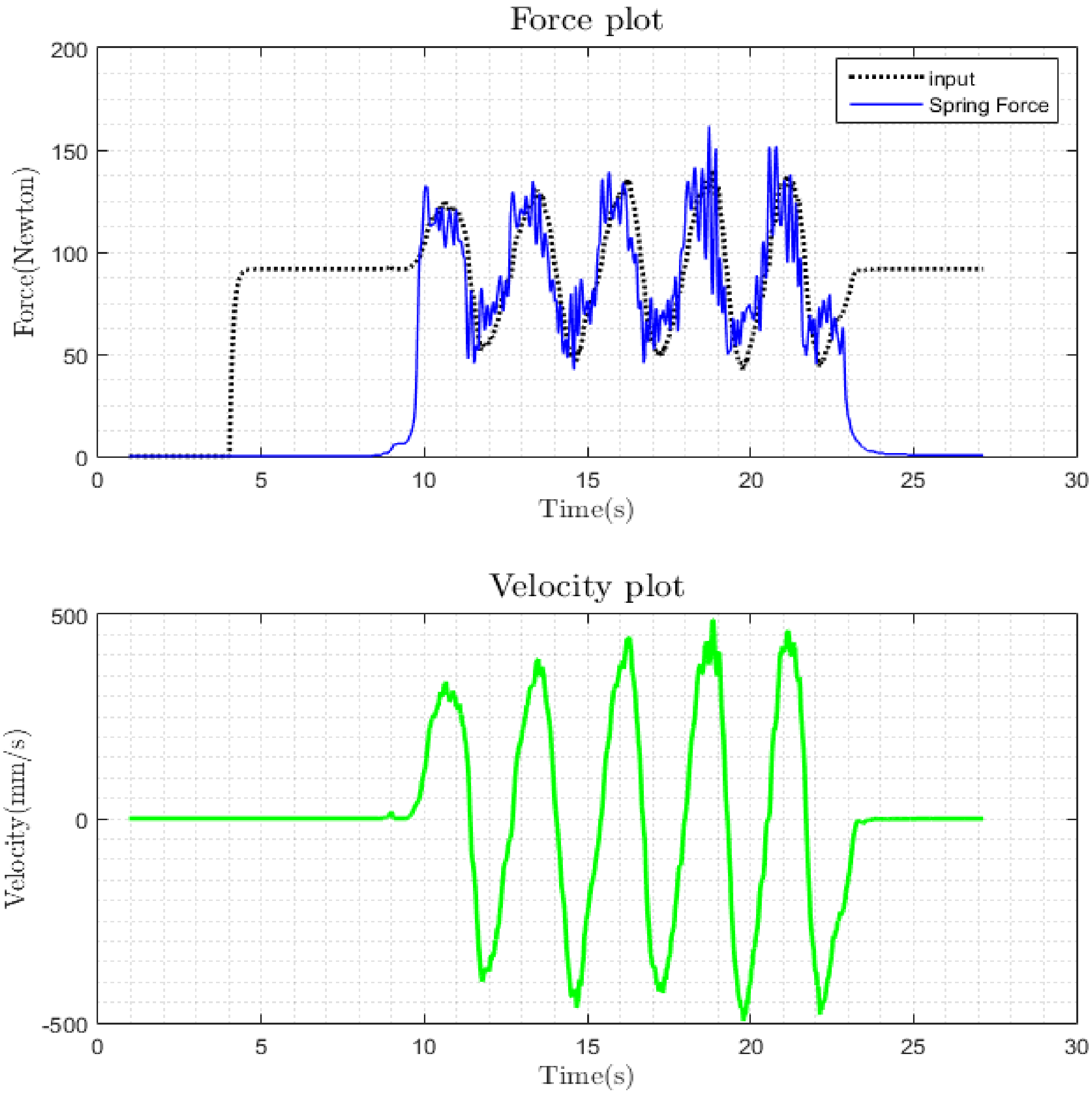

Figure 21. Experiment result of the prototype hardware with $c_v = 100Ns/m$ , $F_c = 10kg$

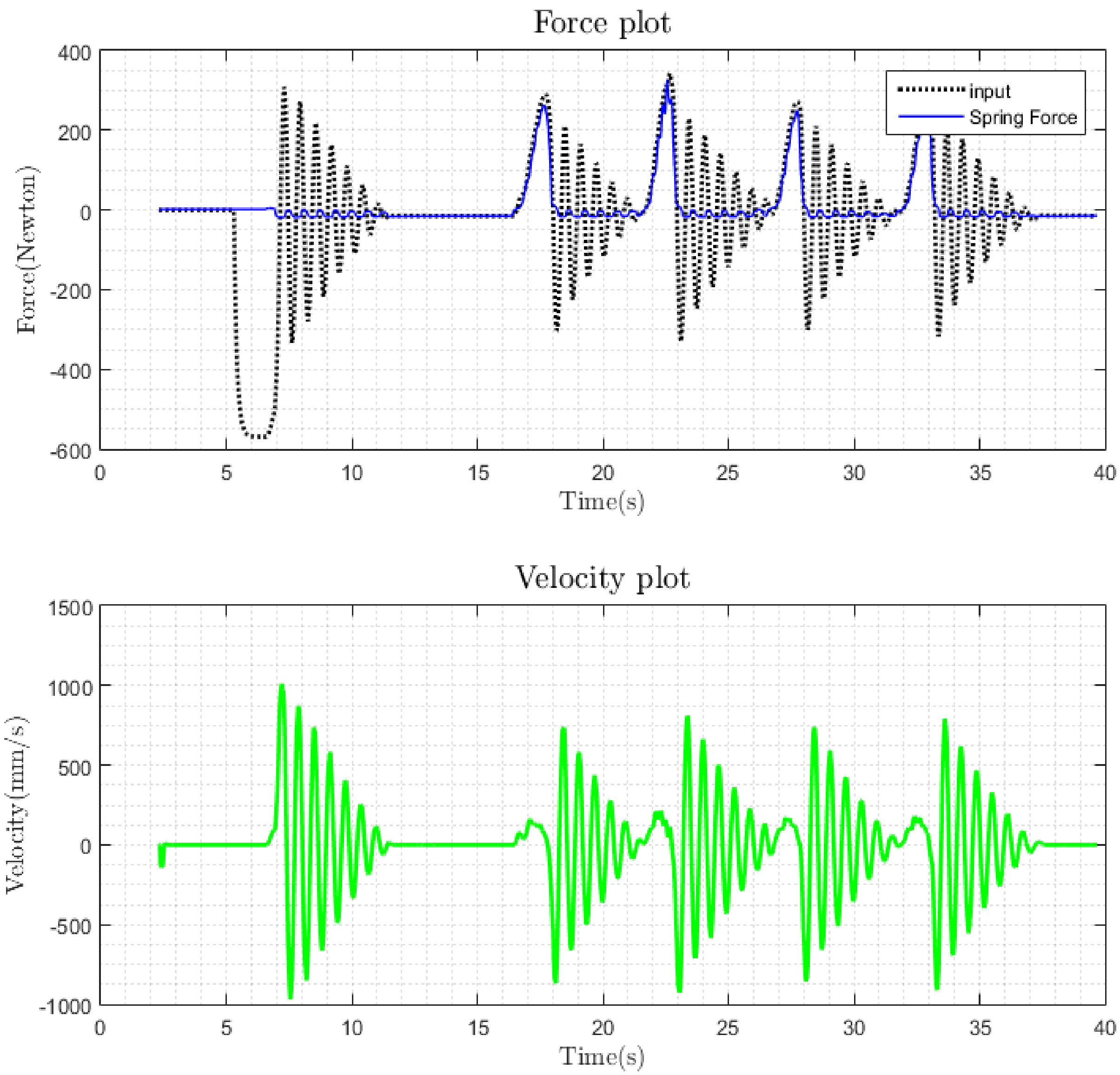

Figure 22. Experiment result of the prototype hardware with $c_v = 100Ns/m, k_v = 2000N/m$

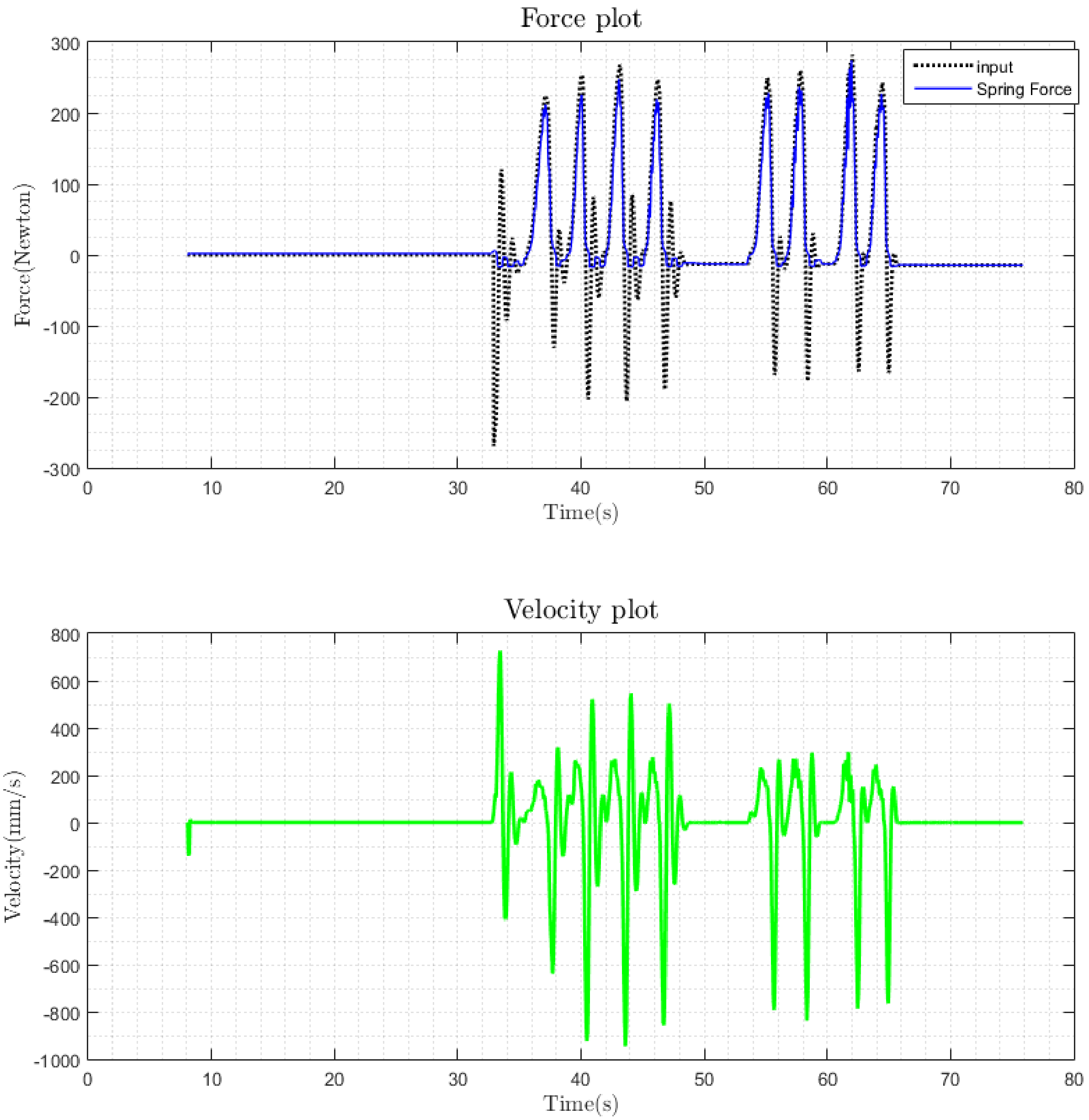

Figure 23. Experiment result of the prototype hardware with $c_v = 100Ns/m, k_v = 1000N/m$

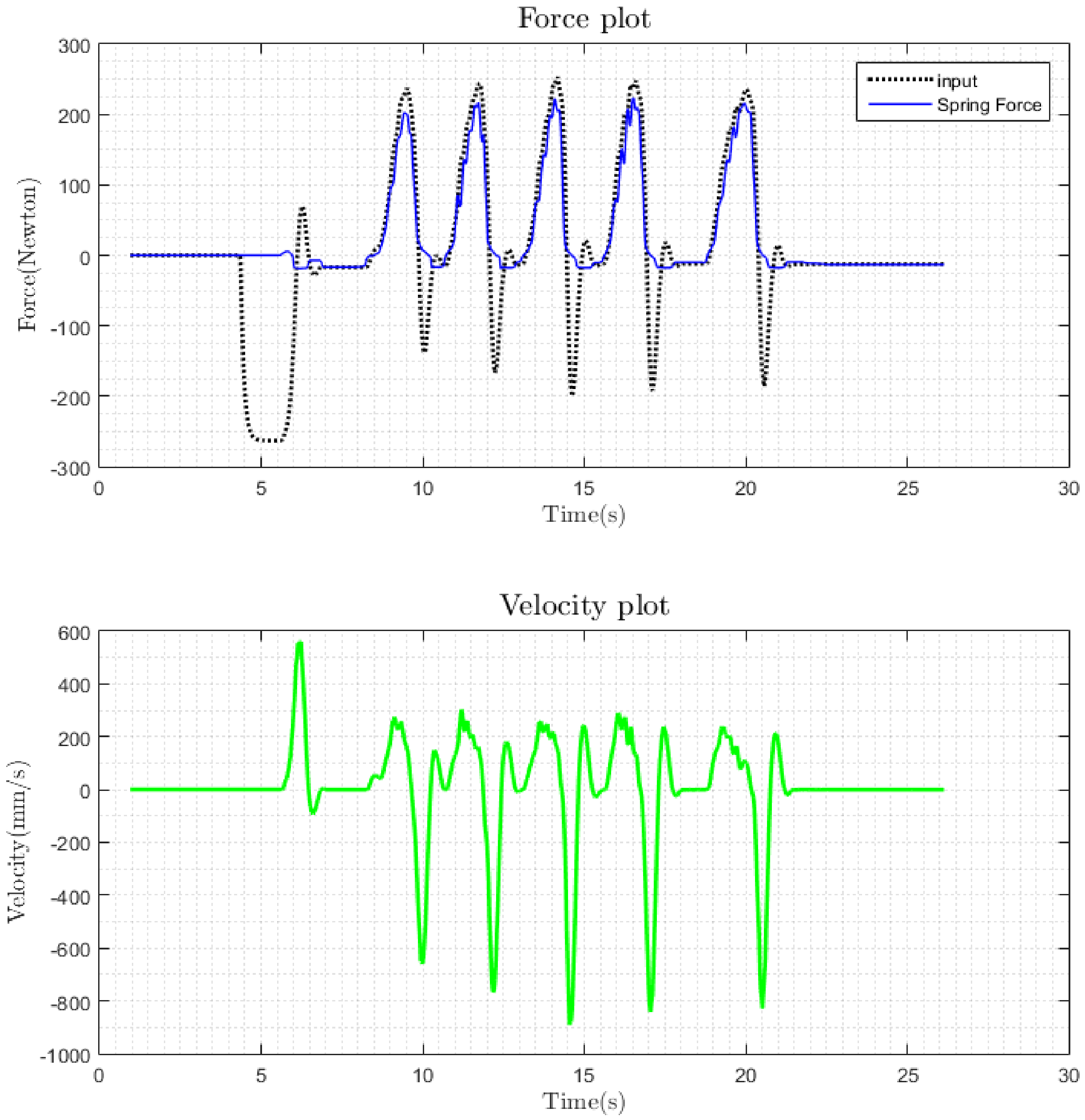

Figure 24. Experiment result of the prototype hardware with $c_v = 200Ns/m, k_v = 1000N/m$

Impedance with a virtual spring and damper were also examined. Three experiments were conducted for following desired force models:

$$F_d = -100\dot{x} + 2000x$$

$$F_d = -100\dot{x} + 1000x$$

$$F_d = -200\dot{x} + 2000x$$

The experiments were performed by pulling and releasing the handles to test the behavior of the system with the different stiffness and damping coefficient. By pulling the cable, the spring force was increased depending on the travel distance, and when the handle was released, the cart oscillated. The results in Figure 22, 23, and 24 clearly demonstrate that the dynamic behavior was changed by adjusting the value of the virtual stiffness and damping.

In conclusion, the experiment results show that the prototype hardware was not only able to track a constant input but also succeeded in simulating a virtual impedance.

# Chapter 7

# Conclusion and Future Work

A motorized exercise machine with a novel force control mechanism was developed by introducing a series elastic actuator to control resistance force. By measuring resistance force with a deformation of spring instead of a load cell, it was possible to develop a motorized exercise machine that has benefits of safety and low manufacturing cost. The prototype hardware was designed to replace weight stacks of conventional exercise machines. A DC motor was used to control the deflection of the spring during an exercise sequence. An Arduino MEGA 2560 board with $16MHz$ clock speed was applied as a Micro Controller Unit and a PWM DC motor speed driver was used to control the speed of the motor. In addition, a user-interface to set resistance levels and receive log data was developed with an Android smartphone application.

Under friction compensation using a viscous friction model, the spring force was considered as a resistance force. Resistance force control was achieved through applying a PID controller to eliminate the error between desired input and measured force.

Moreover, an impedance controller was introduced to provide not only a constant resistance force, but also the effect of a virtual mass, damper and spring for rehabilitation and various training strategies.

The design and control strategy of the prototype were verified through dynamic simulations and physical hardware experiments. Co-simulation of MSC Adams and MATLAB/Simulink was applied to simulate a virtual model of the prototype and test the control algorithm. In addition, the proposed mechanism was compared with the conventional exercise method with weight stacks. Dynamic simulation results showed that the mechanism is able to track a desired resistance force while A conventional system showed force fluctuation because of inertial effects.

Two sets of experiments were conducted to validate the performance of the prototype hardware. The first set of experiments was to show force control capability of the prototype hardware with a constant input resistance force of $10kg, 20kg$ and $30kg$. The results show that it was able to track the input with some errors arising from a change in direction of the stroke because the influence of the acceleration. The imperfect model of the friction force was also generated a fluctuation, while the low sample rate of the Arduino board and oscillation of the base where the prototype was installed cause undesirable noise. The second set of experiments demonstrates the effects of variable impedance input. It is clear that the prototype was able to simulate virtual damping and spring force through impedance control scheme. Therefore, the proposed control algorithm is also possible to be applied as a rehabilitation device for the injured or elderly people.

For further research, it is required to develop more elaborate control strategy to improve force control capability. Since an effect of friction and acceleration of the exercise movement were considered as main reasons of the control error, a better friction compensation method and speed feedback controller need to be applied. In addition, since the purposed mechanism is capable of providing a programmable resistance force, an optimal resistance force profile will be developed by considering the neuromuscular characteristics of humans. For example, electromyography(EMG) measurement can be used for feedback by measuring muscle fatigue to further improve the effect of resistance training.

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