Dynamic Dumbbell - Novel Training Machine with Programmable Exercise Load

Chan Lee and Sehoon Oh
Department of Robotics Engineering
DGIST (Daegu Gyeongbuk Institute of Science and Technology)
Daegu, Korea 711-785
Email: {chanlee, sehoon}@dgist.ac.kr

***Abstract*—A novel robotic device, Dynamic Dumbbell is developed for advanced physical exercise in this paper. The exercise load for muscle training is categorized and formulated in terms of mechanical engineering to be analyzed and implemented in Dynamic Dumbbell. The mathematically formulated exercise load, which is named as programmable exercise load, is realized by Dynamic Dumbbell. To accurately realize the programmable exercise load, compact Planetary-geared Elastic Actuator(cPEA) which is a rotary Series Elastic Actuators is employed for Dynamic Dumbbell, and the torque generated by cPEA is controlled using high performance force control algorithm.**

I. Introduction

Recently, as aging population has become a serious issue in many countries, physical exercise is considered as an important solution to this problem. However, the technology for the exercise still stays in the old ways and there are not so many engineering supports or robotic devices targeting at physical exercises. Even though several researchers in the fields of sports science and biomechanics have came up with some methods to achieve maximum exercise effect in a short time [1], there is much room for robotic engineering to make contributions.

In the sports training field, as a result of these efforts, methods of increasing the performance by using various types of exercise loads are presented. In the past, free weight was traditionally used to stimulate the muscles to exercise. Recently, however, attempts have been made to add loads such as chains and belts or to create more specific types of loads through mechanical design [2].

To analyze and improve the quality and efficiency of the exercise, many biomechanical studies have investigated the characteristics of muscle forces based on various muscle contraction models [3], [4]. Isometric, Isotonic and Isokinetic contractions are representative muscle contraction models [5]: isometric contraction means a muscle contraction that generates tension forces in a stationary muscle length state. Isotonic contraction means a muscle contraction that generates a constant tension force regardless of muscle length change. Isokinetic contraction is a muscle contraction at a constant rate of change of muscle length [6].

The type of exercise load also can be categorized, following these muscle contraction types: isotonic exercise, isometric exercise and isokinetic exercie. Among these three types of exercise, isokineitc exercise has attracted people's attractions recently, and several types of machines have been developed to realize isokinetic exercise [7], [8]. The products by Biodex and Cybex, which employ dampers to limit the speed are widely utilized as Isokinetic exercise devices.

Meanwhile, robotic devices also have been developed to help and support some physical exercises. ETH developed a rowing-machine wire driving system with force control[9]. Korea University introduced a two-degree-of-freedom upper limb exercise robot[10] and used it to analyze muscle activity[11]. All of these robotic devices have used a force sensor to realize force feedback control, which is considered to have several drawbacks; the force sensors are expensive and tend to be bulky and fragile.

Series Elastic Actuator(SEA) has been developed to overcome these drawbacks[12]. SEA places an elastic element between the load and the motor so that the interactive force between the motor and the load can be measured and controlled through the deformation of the elastic element. The SEA can provide relatively inexpensive and accurate force measurement and control. Moreover, shock absorbing ability due to the inherent compliance of the elastic element is considered a significant advantage of SEA to improve safety.

A device for controlling the exercise load using the advantages of SEA has recently been proposed[13]. The 1-degree-of-freedom(DOF) exercise device in [13] adopts a wire tension to provide exercise load, which is controlled by a linear motor through a spring. Even though the application of SEA force control to exercise device is novel and interesting, the device has only one degree of freedom, and the methodology to design exercise load is not thoroughly discussed.

This paper proposes a novel two dimensional robotic exercise device, Dynamic Dumbbell, which is driven by SEAs. In addition to this novel device, a design methodology for programmable exercise load is given. To this end, the three types of exercise load are re-defined from the viewpoint of mechanical engineering, and the way to realize the load using SEA is proposed.

II. Design of Dynamic Dumbbell

Figure 1 illustrates the proposed Dynamic Dumbbell, which is a two-link robot arm consisting of a four-bar linkage driven by two SEAs. It is true that conventional dumbbell exercise is conducted in three-dimensional space without any constraint.

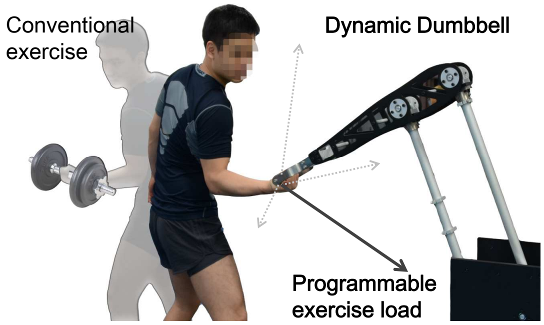

Fig. 1: Illustration of proposed Dynamic Dumbbell

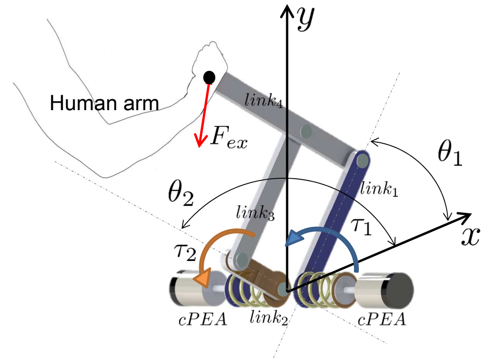

Fig. 2: Coordinate and configuration of Dynamic Dumbbell

When focusing the motion during exercise, however, the arm motion can be considered restricted in two-dimensional plane. Taking this point into account, the proposed Dynamic Dumbbell is designed to provide exercise load in two-dimensional space. Notice that additional passive joints can be implemented in Dynamic Dumbbell to increase the degrees of freedom at the endpoint, which is not included in this paper.

The most significant feature of Dynamic Dumbbell is that it is driven by two SEAs and precise force control is available. To explore the features of Dynamic Dumbbell, the dynamic characteristics of Dynamic Dumbbell is explained in Sec. II-A. Section II-B briefly reviews the structure and characteristics of the SEA utilized in Dynamic Dumbbell.

Figure 2 is a schematic diagram illustrating the mechanism of Dynamic Dumbbell. Parallel mechanism, instead of serial links, is adopted for Dynamic Dumbbell for two reasons. Thanks to this mechanism, the actuator unit (SEA in this paper) can be installed at the base to reduce the mass of arms, and the dynamics of the mechanism can be simplified as follows.

The dynamics of Dynamic Dumbbell shown in Fig. 2 is derived as follows[14].

$$\begin{bmatrix} \tau_1 \\ \tau_2 \end{bmatrix} = \begin{bmatrix} J_{11} & J_{12} \\ J_{21} & J_{22} \end{bmatrix} \begin{bmatrix} \ddot{\theta}_1 \\ \ddot{\theta}_2 \end{bmatrix} + \begin{bmatrix} \tau_{1c} \\ \tau_{2c} \end{bmatrix} + \begin{bmatrix} \tau_{1g} \\ \tau_{2g} \end{bmatrix}, \quad (1)$$

where τ_1 and τ_2 are the torque inputs which are provided by the SEAs. $\ddot{\theta}_1$ and $\ddot{\theta}_2$ are the acceleration values of $link_1$ and $link_2$.

A. Configuration of Dynamic Dumbbell

The elements of the inertia matrix are defined as

$$\begin{aligned} J_{11} &= m_1 l_{1c}^2 + m_3 l_{3c}^2 + m_4 l_4^2 + I_1 + I_3 \\ J_{22} &= m_2 l_{2c}^2 + m_4 l_{4c}^2 + m_3 l_2^2 + I_2 + I_4 \\ J_{12} &= J_{21} = (m_3 l_2 l_{3c} - m_4 l_1 l_{4c}) \cos(\theta_2 - \theta_1), \end{aligned} \quad (2)$$

m_i is the mass of the link i, l_i is the length of $link_i$, and l_{ic} is the distance from the mass center of a link i to the joint i. According to [14] J_{12}, J_{21} along with Coriolis force τ_{1c} and τ_{2c} become 0, when the condition $m_3 l_2 l_{3c} = m_4 l_1 l_{4c}$ is satisfied.

Therefore, the weight and the length of the links are designed to satisfy this condition, which leads to the decoupling of the dynamics of θ_1 and θ_2 and thus the simplification of the dynamics.

τ_{1g} and τ_{2g} in (1) are the effect of gravity on each joint, which are calculated as follows[14].

$$\begin{aligned} \tau_{1_g} &= g \cos\theta_1 (m_1 l_{1c} + m_3 l_{3c} + m_4 l_1) = G_1 \cos\theta_1 \\ \tau_{2_g} &= g \cos\theta_2 (m_2 l_{2c} + m_3 l_2 - m_4 l_{4c}) = G_2 \cos\theta_2 \end{aligned} \quad (3)$$

Notice that each gravity torque τ_{1_g} and τ_{2_g} is related only to θ_1 and θ_2 respectively.

B. Series Elastic Actuator Utilized in Dynamic Dumbbell

As explained in Sec. I, SEA is considered more potential actuator to realize desired exercise load, and thus Dynamic Dumbbell adopted SEAs as torque sources. Among various designs of SEAs, compact Planetary-geared Elastic Actuator (cPEA) is employed as the actuator unit for Dynamic Dumbbell.

cPEA is a rotary SEA with low backlash characteristic and can achieve high force control performance up to 20Hz frequency bandwidth[15]. cPEA consists of a two-stage reduction gear as shown in Fig. 3: the motor in cPEA has its own gear with the ratio of $N_m = 13.7959$, and a planetary gear with the ratio $N_l = 9$ is additionally attached to the first gear end. The sun gear is connected to the first gear end, while the ring gear is connected to the ground through a torsional spring. The carrier is connected to the load working as the torque output, and the torque transmitted to the carrier is determined by the motor torque and the spring deformation. The details of the mechanism and dynamic characteristic can be referred to [15].

The motor angle and spring deformation in cPEA are measured by encoders and utilized for feedback control. The transfer function from the motor torque τ_m to the torque τ_{out} generated by the spring can be expressed as follows.

$$P_{cPEA}(s) = \frac{\tau_{out}}{\tau_m} = \frac{-N_m^{-1}(N_l - 1)P_m(s)}{N_m^{-2}P_m(s) + N_l^2 P_l(s) + (N_l - 1)^2 P_s(s)}, \quad (4)$$

where $P_m(s)$ denotes the dynamic characteristics of the motor itself, $\frac{1}{J_m s^2 + B_m s}$, and $P_l(s)$ is the dynamic characteristics of

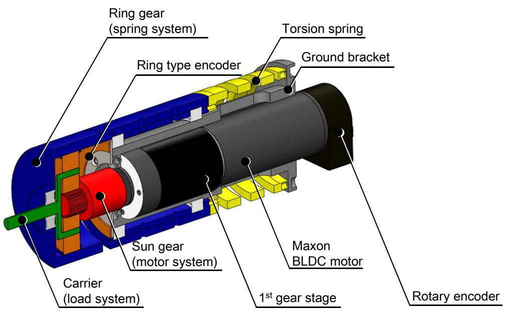

Fig. 3: Compact Planetary-geared Elastic Actuator(cPEA) utilized in Dynamic Dumbbell

the load $\frac{1}{J_l s^2+B_l s}$. $P_s(s)$ represents the dynamic properties of the ring gear and the spring attached from ring gear to the ground, $\frac{1}{J_s s^2+B_s s+K_s}$. $J_\bullet$ represents the moment of inertia, $B_\bullet$ represents the damping coefficient of each part, and K_s is the stiffness of the spring. The high performance force control which will be explained in Sec. III-B is designed utilizing this dynamic model.

III. Programmable Exercise Load and its Realization

This section discusses the types of exercise loads used in the actual training field from a mechanical point of view, and proposes a method to realize programmable exercise load using Dynamic Dumbbell. In other words, it is shown that Dynamic Dumbbell can generate programmable exercise load that matches the contraction models of muscles studied in sports science and biomechanics.

A. Understanding Exercise Load Models from Mechanical Viewpoint

The types of exercise loads used in weight training vary widely; conventionally, exercise has been performed with simple weight loads. Recently, however, the exercise is performed using additional devices other than the weight load, particularly with the popularity of advanced training such as CrossFit. In the wake of these new exercise methods, the exercise loads needs to be categorized and analyzed to better understand the efficiency of the exercise.

In Biomechanics, there have been attempts to classify the kinetic/kinematic characteristics of muscle, and muscle contractions are categorized into Isometric contraction, Isotonic contraction, and Isokinetic contraction. Based on this categorization, exercise loads are also categorized into the same three categories[2] and several devices have been developed to achieve different types of exercise load.

Recently, there has been an attempt to model a specific exercise load from an engineering point of view[16]. That approach, however, could not include the isometric, isotonic and isokinetic exercise loads. In this paper, it is proposed that the different types of exercise loads can be described in a comprehensive way using from the mechanical viewpoint and thus can be programmed/implemented in Dynamic Dumbbell. For this purpose, it is necessary to mathematically formulate the behavior of the muscle contraction.

Three types of muscle contraction can be summarized as follows based on various sports science documents[5][3][17].

1) Isometric contraction refers to the muscle contraction with muscle length constrained.
2) Isotonic contraction means the muscle contraction that generates constant force output.
3) Isokinetic contraction represents the muscle contraction when the rate of muscle length change is limited.

The types of exercise loads are defined corresponding to the muscle contraction types. Isometric exercise load is defined as the exercise load that causes muscles to generate force under the limitation of position deviation. Based on this definition, the isometric exercise load, F^k_{ex}, is supposed to generates forces on the trainee proportionally to the position deviation q as follows.

$$F^k_{ex} = R_k q, \tag{5}$$

where R_k is a proportional adjustable variable, and q is displacement (of joints or any arbitrary motion of the trainee). Exercises using rubber bands can be categorized into this isometric exercise[16]. It is also possible to induce the ideal isometric contraction by setting R_k to a very large number, which will provide a reaction force mimicking a stiff environment such as a wall.

Isotonic exercise load is defined as the load that causes muscle to generate constant force regardless of position and velocity of motions. The conventional weight lifting exercise such as dumbbell can be categorized into this exercise. The isotonic exercise load, F^m_{ex}, can be described as follows.

$$F^m_{ex} = R_m g, \tag{6}$$

where R_m is an adjustable mass of the weight load, and g is the gravitational acceleration[16]. The load model of a actual dumbbell should include the inertial force term $R_m \ddot{q}$ which varies according the the acceleration $\ddot{q}$. However, due to the nature of the isotonic contraction defined as above, the load is considered to maintain constant during exercise, and thus the load caused by the acceleration is excluded in the proposed isotonic exercise model.

Isokinetic exercise is supposed to provide loads on muscles as well as velocity limitations. A damper can be utilized to generate a force to constrain the velocity and thus isokinetic exercise load. The isokinetic exercise load, F^b_{ex}, can be formulated as follows.

$$F^b_{ex} = R_b \dot{q}, \tag{7}$$

where R_b is an adjustable damping variable that determines the amount of the isokinetic exercise. When this load is applied, the maximum speed of the motion will be limited up to $\frac{F^{max}_h}{R_b}$ with the maximum human force F^{max}_h generated during exercise.

These exercise loads can be comprehensively represented by the block diagram shown in Fig. 4 where M_h is the mass

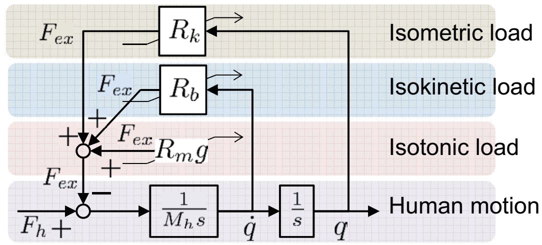

Fig. 4: Block diagram representation of programmable exercise load

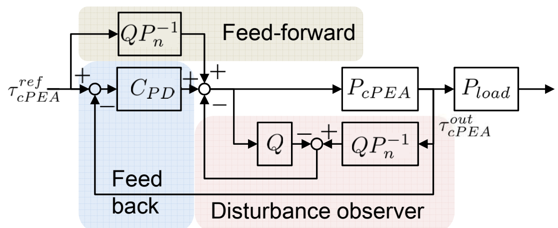

Fig. 5: Block diagram of robust force controller for cPEA

of the human limb. Equation (8) is the general formulation of the exercise load that can describe all exercise load types.

$$F_{ex} = R_b\dot{q} + R_k q + R_m g \tag{8}$$

The exercise load F_{ex} given as in (8) is defined as programmable exercise load that includes all the characteristics of isometric, isotonic and isokinetic exercise loads. By adjusting variables R_m, R_b and R_k, any types of exercise load can be programmed and realized using the proposed Dynamic Dumbbell.

B. Robust Force Control for Realization of Exercise Load

SEA in Dynamic Dumbbell should be able to generate programmable exercise load F_{ex} accurately. PID controllers which are generally used for force control of SEAs, cannot guarantee the tracking performance particularly when environment changes. To address this issue, a robust force control algorithm [18] is adopted in this paper. Figure 5 illustrates the block diagram of the robust force control.

The control algorithm consists of the disturbance observer(DOB) to remove the model uncertainty caused by external environment changes, a feedforward(FF) controller to improve tracking performance and PD controller as a feedback controller. The nominal model $P_n(s)$ used in DOB and FF is derived from the dynamic model $P_{cPEA}(s)$ in (4). The PD controller is applied as an additional controller for tuning the performance of force control. The model parameters and control parameters used in this paper can be referred to [15].

Experiments were conducted on $link_1$ of Dynamic Dumbbell to verify the performance of the force control. Tracking performance of the controller was experimented with a step reference of 30N at 3 second. One second after the reference was given, a person hold the end point of $link_1$ and oscillated it for 3 seconds to create dynamic motions. The contact force during the experiment was measured by a force sensor installed between the end point of $link_1$ and the human hand.

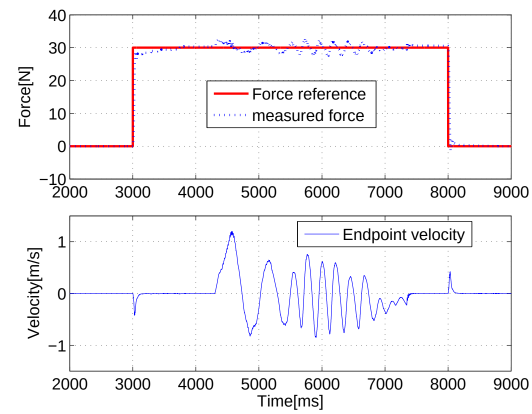

Fig. 6: Force control performance verification of cPEA

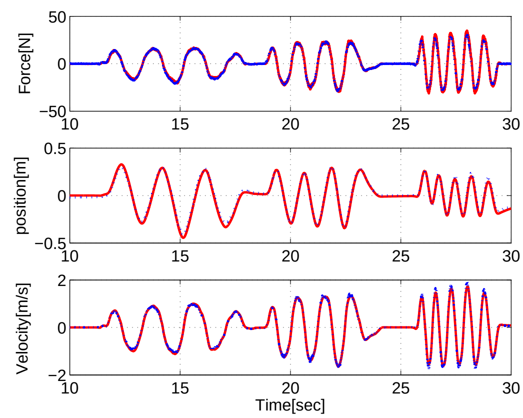

Fig. 7: Programmable exercise load control performance

The results is shown in Fig. 6. In the upper graph of Fig. 6, the red solid line shows the force reference, and the blue dotted line shows the measured contact force. The lower graph of Fig. 6 shows the velocity of the end point of $link_1$. The result validates that the tracking error is not very large even during dynamic motions; the maximum error during dynamic motions is around 2.85N, which is less than 10 $\%$ of the reference.

The ability of Dynamic Dumbbell to generate the programmable exercise load is also verified through experiments. At first, the exercise load is designed as

$$F_{ex}^{exp} = 20\dot{q} + 10q. \tag{9}$$

q in this experiment is set to θ_1 in Fig. 2, the angle of $link_1$, which is measured by an encoder. Then F_{ex}^{exp} calculated as in (9) is given as the force reference τ_{cPEA}^{ref} to cPEA.

In order to verify whether Dynamic Dumbbell correctly implements the exercise load model of F_{ex}^{exp}, the force, velocity and position of Dynamic Dumbbell are measured and compared with the computer simulation which simulates the model in (9).

Figure 7 shows the comparison, where the red solid lines on each graph are the values from the simulation, and the blue dotted lines are the actual measurements. The matches between two signals verify that the proposed Dynamic Dumbbell can accurately generate exercise load as designed.

C. Two Dimensional Exercise Load Design

The programmable exercise load defined in (8) can be extended to a two-dimensional system as long as SEAs can generate desired torques on each joint.

Jacobian matrix of Dynamic Dumbbell is required to convert the joint level torques to the end effector level force. Jacobian from the joint coordinate system to the absolute coordinate system of the end effector as illustrated in Fig. 2 is calculated as follows.

$$\boldsymbol{J} = \begin{bmatrix} -l_1 \sin\theta_1 & -l_4 \sin\theta_2 \\ l_1 \cos\theta_1 & l_4 \cos\theta_2 \end{bmatrix} \tag{10}$$

Note that l_1 and l_4 are designed to be the same length $l =$ 600mm in the proposed Dynamic Dumbbell. Using the $\boldsymbol{J}$, the exercise load supposed to be generated at the end effector of Dynamic Dumbbell is converted to the joint level torque reference as follows.

$$\begin{bmatrix} \tau_{cPEA.1}^{ref} \\ \tau_{cPEA.2}^{ref} \end{bmatrix} = \boldsymbol{J}^T \boldsymbol{F_{ex}} = l \begin{bmatrix} -F_{ex}^x \sin\theta_1 + F_{ex}^y \cos\theta_1 \\ -F_{ex}^x \sin\theta_2 + F_{ex}^y \cos\theta_2 \end{bmatrix} \tag{11}$$

The exercise load $\boldsymbol{F}_{ex}$ in two dimensions can be designed to provide independent exercise load in each direction. Equation (12) is the formulation of the two dimensional exercise load $\boldsymbol{F}_{ex}$ to achieve this.

$$\boldsymbol{F_{ex}} = \begin{bmatrix} F_{ex}^x \\ F_{ex}^y \end{bmatrix} = \begin{bmatrix} R_b^x \dot{P}_x + R_k^x P_x + R_m^x g \\ R_b^y \dot{P}_y + R_k^y P_y + R_m^y g \end{bmatrix} \tag{12}$$

By controlling two SEAs in Fig. 2 to accurately generate $\tau_{cPEA.1}^{ref}$ and $\tau_{cPEA.2}^{ref}$, the programmed exercise load $\boldsymbol{F}_{ex}$ can be realized in Dynamic Dumbbell. With the compensation of the influence of gravity on Dynamic Dumbbell based on (3), the trainee feels the following exercise load by moving the end of Dynamic Dumbbell.

$$\begin{bmatrix} F_h^x \\ F_h^y \end{bmatrix} = \begin{bmatrix} (M_h^x + M_r^x)\ddot{P}_x + R_b^x \dot{P}_x + R_k^x P_x + R_m^x g \\ (M_h^y + M_r^y)\ddot{P}_y + R_b^y \dot{P}_y + R_k^y P_y + R_m^y g \end{bmatrix} \tag{13}$$

F_h^x and F_h^y are the interactive forces in the x and y directions, which the trainee experiences. M_h^x and M_h^y are the x and y directional masses of the human limb, and M_r^x and M_r^y are the x and y directional masses of the robot link. Accelerate feedback can be used to compensate for the inertial forces[19].

IV. Conclusion

The contributions of this paper are as follows.

1) The concept of Dynamic Dumbbell, a 2-DOF exercise robotic device, was introduced.
2) Based on the muscle contraction characteristics, exercise load was categorized and analyzed from mechanical viewpoint.
3) It was shown that Dynamic Dumbbell can realize the proposed programmable exercise load using high performance SEA.

The experimental verification of the improvement of exercise efficiency by Dynamic Dumbbell is the future work.

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