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AN UPPER LIMB EXOSKELETON FOR PINPOINTED MUSCULAR EXERCISES WITH OVEREXTENSION INJURY PREVENTION

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ABSTRACT

Over-automated equipments and modern city life style lead to the diminishing opportunities for muscle using; however, the comfortable life is not always good for human health, and appropriate muscle training can not only enhance muscular strength and endurance but improve the health and fitness. Different kinds of ideas have been proposed for muscle training by exercise machines, which control direction of resistance for safety sake but isolate specific muscle groups to be trained. Compared with machines, free-weight exercise is a whole-body training in which human limbs can be moved on different planes to train more muscle groups. In this study, an upper limb exoskeleton design is proposed for free-weight exercise to strengthen the principal muscles of upper limb and shoulder. The upper limb exoskeleton is constituted of 3-DOF shoulder joint and 1-DOF elbow joint. The joint torques of shoulder and elbow joint of the exoskeleton match the objective joint torques from a model of free-weight exercise. The principal muscles of human arm and shoulder are training by dumbbell lateral raise, dumbbell frontal raise, dumbbell curl motion, and overhead triceps extension motion. With the arrangement of small-inertia springs, the exoskeleton is capable of preventing the muscle from injuries caused by the huge inertia change. The evaluation of the model was conducted by using isokinetic dynamometer to measure shoulder abduction-adduction, shoulder flexion-extension, and elbow flexion-extension for the male and female adults, and the results matched with the data obtained from the derived model.

Keywords: exoskeleton, free-weight exercise, muscular exercise, upper limb

1. INTRODUCTION

Hisamoto, S. and Higuchi, M. (2007) have displayed a report that young people in Japan have less muscle strength than older people based on measuring about 1000 healthy people’s joint torques [1]. The reason is that more over-automated equipments in the recent daily life reduce the opportunities for muscle using. However, the comfortable life is not always good for human health; appropriate muscle training can not only enhance muscular strength and endurance but improve the health and fitness, e.g., reinforcing cardiopulmonary function, reducing body fat, and improving bone mineral density and physical function, etc. [2]. Among muscle trainings, resistance exercise has been widely adopted to help patients recover normal physiological functions in impairing motor activity, improving dynamic stability, etc [3, 4]. The forms of resistance exercise can be classified into static resistance exercise (isometric exercise) and dynamic resistance exercise (isokinetic exercise and isotonic exercise) [5].

Isometric exercise is a training in which muscles can be contracted without moving joints. This exercise is to make muscle fibers in a state of isometric contraction where muscles generate force without changing length. The exercise is performed beyond the maximum strength of an individual when one tries to resist an immovable object. Most studies have been indicated isometric exercise is superior to isokinetic exercise and isotonic exercise in muscle strength gains. Knapik, J. J., et. al (1983) have demonstrated isometric exercise allows training at a maximum output torque [6], and Kuhlman, J. R., et. al (1992) have indicated isometric peak torque is greater than isokinetic peak torque [7]. However, isometric exercise does not improve motor performance ability; the recovery of muscles’ dynamic functions must be through dynamic resistance exercise [5]. Isokinetic exercise is a training in which muscle contracts at a constant angular

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velocity of joint [5]. Thistle, H. G. et. al (1967) have presented the isokinetic exercise by a precise control of velocity movement [8], Kikuchi, T. et. al. (2003) have developed an isokinetic exercise machine by using ER brake [9], and Garner B. A.(2007) has designed a four-bar linkage exercise machine with hydraulic resistance close to isokinetic exercise [10]. The exercise provides the muscles to exert a continual maximal force throughout the range of motion [5]. However, the complexity velocity control systems are difficult to maintain truly constant angular velocity and isokinetic dynamometers do not store potential energy to cause eccentric contraction during the return motion of limb [8]. Even though eccentric contraction is easy to result in muscle damage, the exercise which combines concentric and eccentric contraction can obtain greater gains in muscle strength [5]. Isotonic exercise is a training where the external resistance does not vary during the training process [5]. Isotonic exercise has both concentric and eccentric muscle contraction throughout the range of motion; moreover, isotonic exercise is superior to isokinetic exercise in gains of muscle strength [11]. Therefore, isotonic exercise was chosen to strengthen the muscle force in this study. The idea of using machines instead of free-weights to provide resistances is then developed. An example of machine-assisted exercise in the early years can be found in U.S. patents where an exercising chair has been designed by White, M. V. B.(1879), which strengthens the muscles of arm and chest through resisting the resistance of spring and weight of the exerciser [12]. Most of the machines in U.S. patents use weight stack as the source of resistance, e.g., U.S.4836535 [13], U.S.5336148 [14], and U.S.6152864 [15], while there are some machines which use spring as the source of resistance, such as U.S.5613928 [16] and U.S.7060012 [17]. It requires less skills to control the weight stack than free weight exercise and reduces the possibilities of injury. However, most machines permit movements in a single plane to isolate specific muscle groups for training, but free-weight exercise allows human limbs with external weights moving on different planes to train more muscle groups [2, 18, 19].

In this study, an upper limb exoskeleton design is proposed for free-weight exercise to strengthen the principal muscles of upper limb and shoulder. The upper limb exoskeleton is consisted of 3-DOF shoulder joint and 1-DOF elbow joint where the upper arm can perform the motions of internal-external, abduction-adduction, and flexion-extension, and the forearm is able to carry out flexion-extension motion. The joint torques of shoulder and elbow joint with the upper limb exoskeleton have to equal the objective joint torques obtained from a model of free-weight exercise. The principal muscles of human arm and shoulder are training by dumbbell lateral raise motion, dumbbell frontal raise motion, dumbbell curl motion, and overhead triceps extension. With the arrangement of small-inertia springs, the exoskeleton is capable of preventing the muscles from injuries caused by the huge inertia change. Also, the locations of springs need to be adjusted for higher intensity training. Moreover, the gravitational potential energy including upper limb and exoskeleton would remain constant unlike the situation in free-weight exercise that external weights have been increased to induce huge inertia in heavier muscle strengthening. Finally, in order to be used for different individuals, the link length of exoskeleton is adjustable.

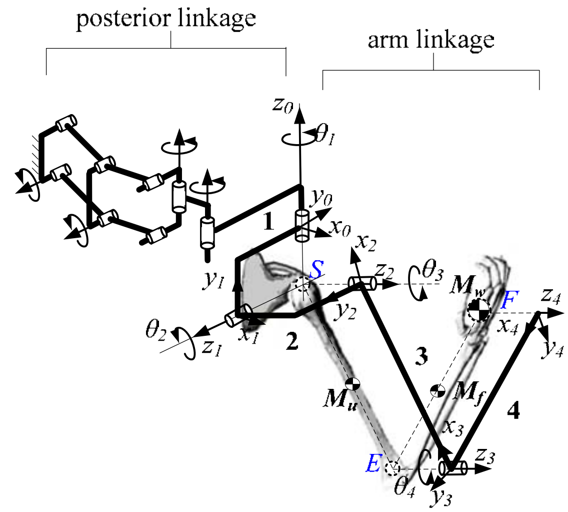


Figure 1 KINEMATIC MODEL AND COORDINATE SYSTEM OF RIGHT UPPER LIMB

2. KINEMATIC MODEL OF UPPER LIMB

An upper limb contains the upper arm and the forearm. The upper arm in Fig. 1 is from the glenohumeral (GH) joint *S* to the elbow joint *E*, and the forearm is from the elbow joint *E* to the middle of palm of hand *F*. The mass of a human hand is relatively small compared to the upper limb and the hand is usually at its neutral position in the upper arm movements so that the gravitational variation caused by the wrist motion is negligible. Hence, the upper limb can be modeled as a two-link linkage where the positions of mass centers, M_u and M_f, are assumed to be fixed and located on the center lines of the upper arm and forearm respectively. The kinematic model is shown in the arm linkage in Fig. 1. The glenohumeral (GH) joint in human skeleton connecting scapular and humerus is modeled as a 3-DOF ball joint at point *S*. Kinematically, any Euler angle sequence of three orthogonal rotation axes can be used to model three pure rotations of the GH center point, e.g., the shoulder flexion-extension, abduction-adduction and internal-external rotation. The elbow joint is regarded as a revolute joint at point *E*, which provides the elbow flexion-extension motion only.

The Denavit-Hertenberg (D-H) parameters are often used for the kinematic modeling of the upper limb. Following Denavit and Hertenberg's convention (1955) in Fig. 1, four Cartesian coordinate systems (CSs), CS 1, 2, 3, and 4, are attached to each link, and CS 0 is attached to ground. The 4×4 D-H transformation matrix between links *i* and *i-1* can be represented as

$$ {}^{i-1}\boldsymbol{T_i} = \begin{bmatrix} c\theta_i & -c\alpha_i s\theta_i & s\alpha_i s\theta_i & a_i c\theta_i \\ s\theta_i & c\alpha_i c\theta_i & -s\alpha_i c\theta_i & a_i s\theta_i \\ 0 & s\alpha_i & c\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1) $$

where the a_i and d_i are the common normal between axes x_i and x_{i-1} and between z_i and z_{i-1}, respectively, α_i is the angle measured from z_{i-1}-axis to z_i-axis about x_i-axis, and θ_i is the joint angle from axis x_{i-1} to x_i about axis z_{i-1}, abbreviations $c\theta_i$

Table 1 D-H PARAMETERS FOR THE UPPER LIMB

Frame i	d_i	θ_i	a_i	α_i
1	0	θ_1	0	90°
2	0	θ_2	0	90°
3	0	θ_3	$-r_{SE}$	0
4	0	θ_4	$-r_{EF}$	0

and $s\theta_i$ are used for $\cos(\theta_i)$ and $\sin(\theta_i)$, respectively, throughout the paper for the conciseness.

From Fig. 1, the origins of CSs 0, 1, and 2 are coincident at GH joint S whose corresponding d_i and a_i are zeros. θ_1, θ_2, θ_3 and θ_4 represent the rotation angles of shoulder internal-external, shoulder abduction-adduction, shoulder flexion-extension, and elbow flexion-extension motions respectively. Where r_{SE} is the segmental length of the upper arm measured from the shoulder pivot to the elbow pivot, and r_{EF} is the segmental length of the forearm measured from the elbow pivot to the middle of palm. The D-H parameters are listed in Tab. 1.

The inside portion of a human shoulder is called shoulder girdle, which is consisted of clavicle and scapular. The clavicle is connected to the trunk by sternoclavicular joint, and the glenohumeral (GH) joint connects scapular and humerus. The motion of shoulder girdle is enabled by the scapulothoracic, sternoclavicular and acromioclavicular joint. Klopčar, N. et. al. (2005) have indicated the girdle motion can be modeled as two degrees of freedom by using a universal joint and a dependent translation [20]. The motion of girdle is enabled by two parallelogram linkages and two serially connected links, and the assembly is shown in the posterior linkage in Fig. 1. The parallelogram linkages provide the girdle a superior-inferior motion vertically, and the two serially connected links allow the GH center to be free on a horizontal plane.

The muscles on the shoulder are complicated; the deltoid muscles are the principal muscles on the shoulder. Deltoid muscles contain anterior deltoid, middle deltoid and posterior deltoid, encircling the shoulder joint and acting in most shoulder movements. Besides, there are rotator cuff act to stabilize the shoulders where the rotator cuff is a muscle group formed by suparaspinatus, infraspinatus, teres minor and subscapularis muscle. In the back of a human, latissimus dorsi has functions to raise an arm, and there is pectoralis major muscle in the chest of a human body. There are biceps and triceps on the upper arm where the former contributes more when forearm is flexed, and the latter has contributions on the elbow extension. In free-weight exercises, dumbbell exercises are commonly used to train the muscles of shoulder and upper arm. According to degrees of freedom of shoulder in this study, dumbbell bench fly, dumbbell lateral and frontal raise motions are corresponding to shoulder internal-external, abduction-adduction, and flexion-extension motion, respectively. The dumbbell bench fly is an exercise for strengthening the pectoralis major muscles, while anterior deltoid and biceps provide synergy during the exercise. The lateral raise motion can strengthen the muscles of deltoid, suparaspinatus, latissimus dorsi and pectoralis major. The frontal raise motion is a training mainly about the muscles of coracobrachialis, deltoid muscle, pectoralis major, and latissimus dorsi. There is

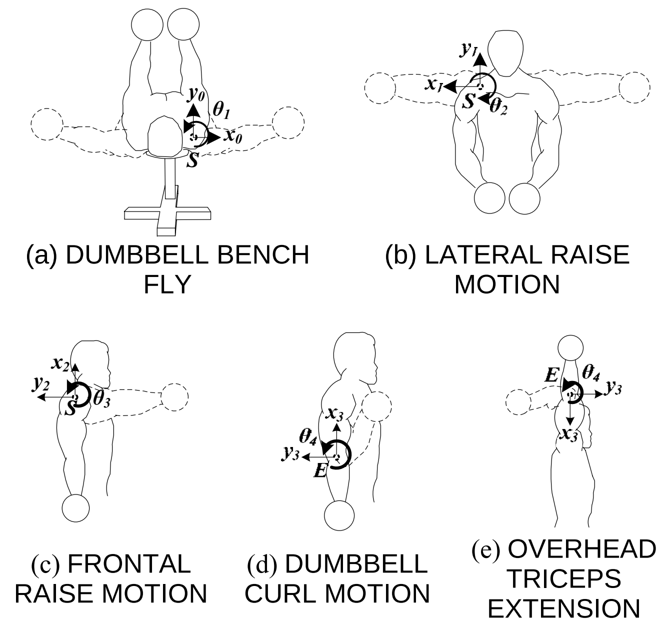


Figure 2 DUMBBELL EXERCISES

dumbbell curl motion around the axis of elbow flexion-extension which principally trains biceps as well as brachialis and brachioradialis. The triceps brachii is an extensor muscle group which works in the extension movements of upper limb, (i.e., shoulder abduction, shoulder extension, and elbow extension) but its contributions are not significant. For major training triceps, an overhead triceps extension is achieved by rotating the forearm about axis of elbow flexion-extension [21, 22].

3. JOINT TORQUES OF FREE-WEIGHT EXERCISE

Free-weight exercise is a muscular exercise by using external weights as resistant force on a freely moving body, and then the muscle force would be strengthened by increasing the free-weights load gradually. In Fig. 1, an objective model is constructed for dumbbell exercise where an external load m_w is grasped in the middle of palm F, and the segmental masses of upper arm and forearm, m_u and m_f, are located on the mass centers of upper arm and forearm, respectively. The mass of a human hand can be ignored here because it is relatively light compared to the upper limb. During exercising, the gravitational potential energy of the kinematic model can be expressed as

$$\begin{aligned} & V_{g,obj} \\ & = -m_u \boldsymbol{g}\cdot(\boldsymbol{r_{SE}}+\boldsymbol{r}_u) - m_f \boldsymbol{g}\cdot(\boldsymbol{r_{SE}}+\boldsymbol{r}_{EF}+\boldsymbol{r}_f) \\ & \quad - m_w \boldsymbol{g}\cdot(\boldsymbol{r_{SE}}+\boldsymbol{r_{EF}}+\boldsymbol{r}_w) \\ & = -m_u(-g\boldsymbol{k_0})\cdot(-\boldsymbol{r_{SE}}\boldsymbol{i_3}+\boldsymbol{r}_{u,x}\boldsymbol{i_3}) \\ & \quad - m_f(-g\boldsymbol{k_0})\cdot(-r_{SE}\boldsymbol{i_3}-r_{EF}\boldsymbol{i_4}+r_{f.x}\boldsymbol{i_4}) \\ & \quad - m_w(-g\boldsymbol{k_0})\cdot(-r_{SE}\boldsymbol{i_3}-r_{EF}\boldsymbol{i_4}) \end{aligned} \tag{2}$$

where r_u, r_f and r_w are the mass center position vectors of M_u, M_f, and m_w referenced on each corresponding CSs. Quantities $r_{u,x}$, $r_{u,y}$, $r_{u,z}$, $r_{f,x}$, $r_{f,y}$, $r_{f,z}$, $r_{w,x}$, $r_{w,y}$, and $r_{w,z}$ are the corresponding local coordinates. Note that, the geometries of the upper arm and the forearm are assumed axially symmetric and thus, quantities $r_{u,y}$ and $r_{f,y}$ are omitted in Eqn.(2). For CS0, quantities $r_{u,z}$, $r_{f,z}$ and $r_{w,z}$ are zero. The mass center position of m_w is assumed on point F, quantities $r_{w,x}$ and $r_{w,y}$ are zero.

Derived from the D-H transformation matrix,

$$\boldsymbol{k_0} = (s\theta_2)\boldsymbol{i_2} + (-c\theta_2)\boldsymbol{k_2} \quad (3)$$

$$\boldsymbol{k_2} \cdot \boldsymbol{i_3} = 0 \quad (4)$$

$$\boldsymbol{k_2} \cdot \boldsymbol{i_4} = 0 \quad (5)$$

$$\boldsymbol{i_2} \cdot \boldsymbol{i_3} = c\theta_3 \quad (6)$$

$$\boldsymbol{i_3} \cdot \boldsymbol{i_4} = c\theta_4 \quad (7)$$

$$\boldsymbol{i_2} \cdot \boldsymbol{i_4} = c(\theta_3 + \theta_4) \quad (8)$$

Substituting Eqns. (3)-(8) into the Eqn. (2) yields the following equation for the total gravitational potential energy of the upper limb with a dumbbell weight is

$$\begin{aligned} V_{g,obj} &= [-m_u g(r_{SE} - r_{u,x}) - (m_f + m_w) g r_{SE}] s\theta_2 c\theta_3 \\ &\quad - [(-m_f g(r_{EF} - r_{f,x}) + m_w g r_{EF}] s\theta_2 c(\theta_3 + \theta_4) \end{aligned} \quad (9)$$

In muscular exercise, external weights provide moments about the pivot joint, but the direction of the torques is opposite to the movement. For maintaining the movements of the upper limb exercise, there is a tendency from the muscle to resist the opposite torques; therefore, whether the muscle exercises or not can be learned from the changes of joint torques. The partial derivatives of the gravitational potential energy with respective to the joint angle θ_i is used for the calculation of the amount of torques. The gravity torque τ_i on the joint i can be obtained as

$$\tau_i = \frac{\partial V}{\partial \theta_i} \qquad i = 1,2,3,4 \quad (10)$$

By definition, the moment arm is a distance from the pivot joint and perpendicular to the acted force. Since the gravitational force on the weighted objects always acts downward, the moment arm on the upper limb in free-weight exercise is always horizontal. During the exercise, rotating the upper arm would vary the moment arm, resulting in the change of joint torque. On the upper limb free-weight exercise, the gravitational potential energy is function of $s\theta_2$, $c\theta_3$ and $c(\theta_3 + \theta_4)$, Eqn.(10) suggests that τ_1 is zero; τ_2, τ_3 and τ_4 vary with θ_2, θ_3 and θ_4, respectively. The gravity joint torques of the upper limb can be derived as

$$\begin{aligned} \tau_{obj,2} &= [-m_u g(r_{SE} - r_{u,x}) - (m_f + m_w) g r_{SE}] c\theta_2 c\theta_3 \\ &\quad - [m_f g(r_{EF} - r_{f,x}) + m_w g r_{EF}] c\theta_2 c(\theta_3 + \theta_4) \end{aligned} \quad (11)$$

$$\begin{aligned} \tau_{obj,3} &= [m_u g(r_{SE} - r_{u,x}) + (m_f + m_w) g r_{SE}] s\theta_2 s\theta_3 \\ &\quad + (m_f g(r_{EF} - r_{f,x}) + m_w g r_{EF}) s\theta_2 s(\theta_3 + \theta_4) \end{aligned} \quad (12)$$

$$\tau_{obj,4} = [m_f g(r_{EF} - r_{f,x}) + m_w g r_{EF}] s\theta_2 s(\theta_3 + \theta_4) \quad (13)$$

4 DESIGN A SPRING-LOADED EXOSKELETON

4.1 Upper Limb Exoskeleton

An upper limb exoskeleton design with spring attachments is illustrated in Fig. 3. The arm linkage is constructed by four links where the 3-DOF shoulder joint is constituted by three revolute joint of axes z_0, z_1 and z_2 which are arranged to be orthogonal to each other, and the fourth DOF on the flexion-extension motion of the forearm can be obtained with a revolute joint of axis z_3. The design of a 4-DOF kinematic chain, illustrated in Fig. 1, contains four links where the link 1 and posterior linkage are connected by a revolute joint of axis z_0, and link 1 and link 2 are connected by the other revolute joint of the axis z_1. In practices, the

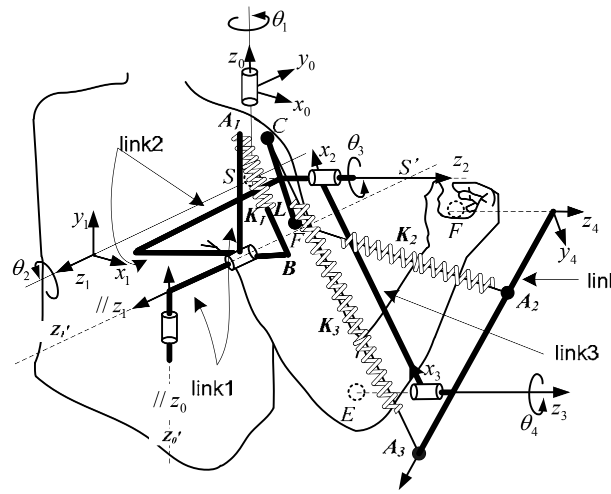


Figure 3 A SPRING LOADED EXOSKELETON FOR PINPOINTED MUSCULAR EXERCISES

exoskeleton configuration in Fig. 1 has drawbacks in the azimuthal rotation limitation which results from the motion interference of link 1 and the back side of the human body as well as in difficulty to achieve the accordance of the joint axes z_0, z_1 and z_2 to the human GH joint center. Hence, the design has been modified to avoid such drawbacks. The link 1 and posterior linkage are connected by a revolute joint of a new axis that parallels z_0-axis, and the new axis of link 1 and link 2 is paralleling z_1-axis. Link 2 and 3 are connected by a revolute joint of axis z_2; links 3 and 4 are attached to the upper arm and forearm respectively and then connected by a revolute joint of axis z_3. Instead of the external weighted objects, the increase of resistant force on the upper limb exoskeleton is achieved by using the spring force. The spring would change the resistance by adjusting the connected locations of spring, but the weight of total exoskeleton remains the same. On the spring-loaded exoskeleton, spring K_1 is attached to point A_1 on link1 and point L on link 2; spring K_2 is attached to point F on link 2 and point A_2 on link 4; spring K_3 is attached to point C on link 2 and point A_3 on link 4. Furthermore, all three springs are made of zero-free length springs. Corresponding to elastic potential energies, $V_{s,1}$, $V_{s,2}$, and $V_{s,3}$ of springs K_1, K_2, and K_3 are derived as

$$\begin{aligned} V_{s,1} &= \frac{1}{2} K_1 (\boldsymbol{l_{LA_1}} \cdot \boldsymbol{l_{LA_1}}) \\ &= (-K_1 l_{LB} l_{SA_1}) s\theta_2 - (K_3 l_{BS} l_{SA_1}) c\theta_2 + const \end{aligned} \quad (14)$$

$$\begin{aligned} V_{s,2} &= \frac{1}{2} K_2 (\boldsymbol{l_{FA_2}} \cdot \boldsymbol{l_{FA_2}}) \\ &= (-K_2 l_{SF} r_{SE}) c\theta_3 + (K_1 r_{SE} l_{EA_2}) c\theta_4 \\ &\quad - (K_2 l_{EA_2} l_{SF}) c(\theta_3 + \theta_4) + const \end{aligned} \quad (15)$$

$$\begin{aligned} V_{s,3} &= \frac{1}{2} K_3 (\boldsymbol{l_{CA_3}} \cdot \boldsymbol{l_{CA_3}}) \\ &= (K_3 l_{SC} r_{SE}) c\theta_3 - (K_3 l_{EA_3} l_{SC}) c(\theta_3 + \theta_4) \\ &\quad - (K_3 l_{EA_3} r_{SE}) c\theta_4 + const \end{aligned} \quad (16)$$

Taking the link masses of the primary chain of the exoskeleton into account, the gravitational potential energy of links 1, 2, 3, and 4 are derived, respectively, as following:

$$\begin{aligned} V_1 &= -m_1 \boldsymbol{g} \cdot \boldsymbol{r_1} \\ &= -m_1(-g\boldsymbol{k_0})(r_{1,x}\boldsymbol{i_1} + r_{1,y}\boldsymbol{j_1} + r_{1,z}\boldsymbol{k_1}) = const \end{aligned} \quad (17)$$

$$V_2 = -m_2 \boldsymbol{g}\cdot \boldsymbol{r}_2 = -m_2(-g\boldsymbol{k_0})(r_{2,x}\boldsymbol{i_2} + r_{2,y}\boldsymbol{j_2} + r_{2,z}\boldsymbol{k_2}) \\ = m_2 g r_{2,x} s\theta_2 - m_2 g r_{2,z} c\theta_2 + const \tag{18}$$

$$V_3 = -m_3 \boldsymbol{g}\cdot \boldsymbol{r}_3 = -m_3(-g\boldsymbol{k_0})(-r_{SE}\boldsymbol{i_3} + r_{3,x}\boldsymbol{i_3} + r_{3,z}\boldsymbol{k_3}) \\ = m_3 g(r_{3,x} - r_{SE}) s\theta_2 c\theta_3 - m_3 g r_{3,z} c\theta_2 + const \tag{19}$$

$$V_4 = -m_4 \boldsymbol{g}\cdot \boldsymbol{r}_4 \\ = -m_4(-g\boldsymbol{k_0})(-r_{SE}\boldsymbol{i_3} - r_{EF}\boldsymbol{i_4} + r_{4,x}\boldsymbol{i_4} + r_{4,z}\boldsymbol{k_4}) \\ = -m_4 g r_{SE} s\theta_2 c\theta_3 + m_4 g(r_{4,x} - r_{EF}) s\theta_2 c(\theta_3 + \theta_4) \\ - m_4 g r_{4,z} c\theta_2 + const \tag{20}$$

where m_i is the mass of link i of the exoskeleton and i is 1, 2, 3, and 4. And $r_{i,x}$, $r_{i,y}$, $r_{i,z}$ describe its corresponding coordinates of the mass center of the link i on local coordinate x_i-y_i-z_i. The link 3 and 4 are assumed to axis-symmetrical links, therefore, $r_{3,y}$ and $r_{4,y}$ can be neglected.

The total gravitational potential energy of the upper limb exoskeleton is expressed as

$$V = V_{upperarm} + V_{forearm} + \sum_{i=1}^{3} V_{S,i} + \sum_{i=1}^{4} V_i \\ = [-m_u g(r_{SE} - r_{u,x}) - m_f g r_{SE} + m_3 g(r_{3,x} - r_{SE}) \\ - m_4 g r_{SE}] s\theta_2 c\theta_3 + (K_2 l_{EA_2} r_{SE} - K_3 l_{EA_3} r_{SE}) c\theta_4 \\ + [-m_f g(r_{EF} - r_{f,x}) + m_4 g(r_{4,x} - r_{EF})] s\theta_2 c(\theta_3 + \theta_4) \\ + (-K_2 l_{EA_2} l_{SF} - K_3 l_{EA_3} l_{SC}) c(\theta_3 + \theta_4) \\ + (-K_2 l_{SF} r_{SE} + K_3 l_{SC} r_{SE}) c\theta_3 \\ + (-K_1 l_{LB} l_{S'A_1} + m_2 g r_{2,x}) s\theta_2 \\ - (K_1 l_{BS'} l_{S'A_1} + m_u g r_{u,z} + m_f g r_{f,z} + m_2 g r_{2,z} \\ + m_3 g r_{3,z} + m_4 g r_{4,z}) c\theta_2 + const \tag{21}$$

The joint torques would be generated by the spring force, and it can emulate real free-weight exercise. Thus, using Eqn. (10), the joint torques of upper limb through the use of the exoskeleton can be derived as

$$\tau_{exo,2} \\ = [-m_u g(r_{SE} - r_{u,x}) - m_f g r_{SE} + m_3 g(r_{3,x} - r_{SE}) \\ - m_4 g r_{SE}] c\theta_2 c\theta_3 + [-K_1 l_{LB} l_{S'A_1} + m_2 g r_{2,x}] c\theta_2 \\ + [-m_f g(r_{EF} - r_{f,x}) + m_4 g(r_{4,x} - r_{EF})] c\theta_2 c(\theta_3 + \theta_4) \\ + [K_1 l_{BS'} l_{S'A_1} + m_u g r_{u,z} + m_f g r_{f,z} + m_2 g r_{2,z} \\ + m_3 g r_{3,z} + m_4 g r_{4,z}] s\theta_2 \tag{22}$$

$$\tau_{exo,3} \\ = [m_u g(r_{SE} - r_{u,x}) + m_f g r_{SE} - m_3 g(r_{3,x} - r_{SE}) \\ + m_4 g r_{SE}] s\theta_2 s\theta_3 + [K_2 l_{SF} r_{SE} - K_3 l_{SC} r_{SE}] s\theta_3 \\ + [m_f g(r_{EF} - r_{f,x}) - m_4 g(r_{4,x} - r_{EF})] s\theta_2 s(\theta_3 + \theta_4) \\ + [K_2 l_{EA_2} l_{SF} + K_3 l_{EA_3} l_{SC}] s(\theta_3 + \theta_4) \tag{23}$$

$$\tau_{exo,4} = [m_f g(r_{EF} - r_{f,x}) - m_4 g(r_{4,x} - r_{EF})] s\theta_2 s(\theta_3 + \theta_4) \\ + [K_2 l_{EA_2} l_{SF} + K_3 l_{EA_3} l_{SC}] s(\theta_3 + \theta_4) \\ - [K_2 l_{EA_2} r_{SE} - K_3 l_{EA_3} r_{SE}] s\theta_4 \tag{24}$$

4.2 Spring Design Conditions for Pinpointed Muscular Exercise

According to 3 DOF of shoulder, there are dumbbell bench fly, dumbbell lateral and frontal raise motions about axes of shoulder internal-external, abduction-adduction and flexion-extension, respectively. In free-weight exercise, dumbbell bench fly is a kind of exercise in which user lies on a bench, and gravity acts on the direction of negative y_0 of CS 0 to provide torques on the shoulder joint about axis of shoulder internal-external motion. However, in this study, only the stand posture is concerned in that when the gravity acts on the direction of negative k_o of CS 0, the torque of shoulder internal-external is zero. Therefore, only dumbbell lateral and frontal raise motions about shoulder abduction-adduction and flexion-extension motion for shoulder joint in the upper limb exoskeleton have been taken into account. Both the two types of dumbbell exercise are able to strengthen deltoid muscle. In elbow flexion-extension motion, there are dumbbell curl motion and overhead triceps extension for principal training biceps and triceps, respectively.

4.2.1 Deltoid Muscle Training from Shoulder Abduction/Adduction. For shoulder abduction-adduction, lateral raise motion is used for strengthening deltoid muscle principally. In free-weight exercise, the prepared posture of a user is upper limb holding the dumbbell at sides of trunk. Then the user's stretching upper limb raises the dumbbell out to sides and keeps the motion on the frontal plane. When the upper limb is parallel to floor, the user returns to the prepared posture and repeats. In the kinematic model, the angles of θ_3 and θ_4 are fixed on 0 degree, and the upper arm and forearm can be considered as one link and the rotating is about axis z_1 with θ_2 only. Substituting the angles θ_3 and θ_4 into Eqns. (11)-(13) yields the joint torques of θ_3 and θ_4 are zero, and then the joint torque of θ_2 can be expressed as

$$\tau_{lr,2} = [-m_u g(r_{SE} - r_{u,x}) - m_f g(r_{SE} + r_{EF} - r_{f,x}) \\ - m_w g(r_{SE} + r_{EF})] c\theta_2 \tag{25}$$

In shoulder abduction-adduction motion with upper limb exoskeleton, the upper limb maintains the same posture as lateral raise motion with exoskeleton; however, the resistance from dumbbells is replaced by springs. Substituting the same angles as lateral raise motion, θ_3 and θ_4, into Eqns. (22)-(24), the joint torques of shoulder with exoskeleton are obtained in which the joint torques of θ_3 and θ_4 are zero, same as lateral raise motion, and the joint torque of θ_2 is shown as

$$\tau_{exo,lr,2} = [-m_u g(r_{SE} - r_{u,x}) - m_f g(r_{SE} + r_{EF} - r_{f,x}) + m_2 g r_{2,x} \\ + m_3 g(r_{3,x} - r_{SE}) + m_4 g(r_{4,x} - r_{EF} - r_{SE}) \\ - K_1 l_{LB} l_{S'A_1}] c\theta_2 \\ + [K_1 l_{BS'} l_{S'A_1} + m_u g r_{u,z} + m_f g r_{f,z} + m_2 g r_{2,z} \\ + m_3 g r_{3,z} + m_4 g r_{4,z}] s\theta_2 \tag{26}$$

For emulating free-weight exercise, the joint torques in lateral raise motion and upper limb exoskeleton have to be equal to each other. As a result, the coefficients of $s\theta_2$ and $c\theta_2$ in Eqns. (25) and (26) must be equal to each other. The design condition of spring K_1 obtained from the equation of coefficients of $c\theta_2$ is expressed as

$$l_{LB} = \frac{m_w g(r_{SE} + r_{EF}) + m_2 g r_{2,x} + m_3 g(r_{3,x} - r_{SE})}{K_1 l_{S'A_1}} \\ + \frac{m_4 g(r_{4,x} - r_{EF} - r_{SE})}{K_1 l_{S'A_1}} \tag{27}$$

Equation (27) represents a function of the weight of dumbbell m_w and the length of connected points of spring K_1 with the only adjustment of l_{LB} to increase the resistant force for training intensity. The links' weights of exoskeleton product momentum about axis z_1' due to the effect of gravity, and by using spring K_1 to compensate the gravitational potential energy of link 2, 3 and 4, the spring design condition of spring K_1 is expressed as

$$l_{BS'} = -\frac{m_u g r_{u,z} + m_f g r_{f,z} + m_2 g r_{2,z} + m_3 g r_{3,z} + m_4 g r_{4,z}}{K_1 l_{S'A_1}} \tag{28}$$

4.2.2 Deltoid Muscle Training from Shoulder Flexion/Extension. For shoulder flexion-extension motion, frontal raise motion is greatly adopted for training deltoid muscles. The beginning of the motion is same as lateral raise motion, holding the dumbbell at sides of trunk, stretching the upper limb, raising the dumbbell directly in front of the user, and keeping the motion on a plane paralleling mid sagittal plane. When the user's upper limb is horizontal, the user backs to the beginning. In the kinematic model, the angles of θ_2 and θ_4 are fixed on 90 and 0 degrees respectively, and the upper arm and forearm can be thought as one rigid body rotating about axis z_2 with θ_3 only. Substituting the angles of θ_2 and θ_4 into the Eqns. (11)-(13) yields the joint torque of θ_2 is zero, and the joint torques of θ_3 and θ_4 can be expressed as

$$\tau_{fr,3} = [m_u g(r_{SE} - r_{u,x}) + m_f g(r_{SE} + r_{EF} - r_{f,x}) + m_w g(r_{SE} + r_{EF})] s\theta_3 \quad (29)$$

$$\tau_{fr,4} = [m_f g(r_{EF} - r_{f,x}) + m_w g r_{EF}] s\theta_3 \quad (30)$$

In shoulder flexion-extension motion with upper limb exoskeleton, user moves same posture as frontal raise motion. Substituting the same angles, θ_2 and θ_4, of frontal raise motion into the Eqns. (22)-(24), the joint torques of shoulder with exoskeleton are obtained, and the joint torques of θ_2, θ_3 and θ_4 are shown as

$$\tau_{exo,fr,2} = K_1 l_{BS'} l_{S'A_1} + m_u g r_{u,z} + m_f g r_{f,z} + m_2 g r_{2,z} + m_3 g r_{3,z} + m_4 g r_{4,z} \quad (31)$$

$$\tau_{exo,fr,3} = [m_u g(r_{SE} - r_{u,x}) + m_f g(r_{SE} + r_{EF} - r_{f,x}) - m_3 g(r_{3,x} - r_{SE}) - m_4 g(r_{4,x} - r_{EF} - r_{SE}) + K_2 l_{SF}(r_{SE} + l_{EA_2}) + K_3 l_{SC}(l_{EA_3} - r_{SE})] s\theta_3 \quad (32)$$

$$\tau_{exo,fr,4} = [m_f g(r_{EF} - r_{f,x}) - m_4 g(r_{4,x} - r_{EF}) + K_2 l_{EA_2} l_{SF} + K_3 l_{EA_3} l_{SC}] s\theta_3 \quad (33)$$

In shoulder flexion-extension motion, the momentum about the axis z_1' due to weights of upper limb exoskeleton's links is same as the momentum in shoulder abduction-adduction motion. Therefore, the design spring conditions of spring K_1 is used and shown in Eqn. (28). For reaching the effects of frontal raise motion, the joint torques in upper limb exoskeleton must be the same as the joint torques in frontal raise motion. Consequently, the coefficients of $s\theta_3$ in Eqns. (29) and (30) must be equal to Eqns.(32) and (33). The design conditions of spring K_2 and K_3 are obtained as

$$l_{EA_3} = 0 \quad (34)$$

$$l_{EA_2} = r_{EF} \quad (35)$$

$$l_{SC} = \frac{-m_3 g r_{EF}(r_{3,x} - r_{SE}) + m_4 g r_{SE} r_{4,x}}{K_3 r_{SE} r_{EF}} \quad (36)$$

$$l_{SF} = \frac{m_w g r_{EF} + m_4 g(r_{4,x} - r_{EF})}{K_2 r_{EF}} \quad (37)$$

In regarding to the shoulder flexion-extension motion for training deltoid muscles, the installation of spring K_1 in l_{LB} length can be set on any position in that it will not affect the results of muscle strengthening.

4.2.3 Biceps and Triceps Training from Elbow Flexion/Extension. For elbow flexion-extension motion, dumbbell curl motion principal is a biceps strengthening in free-weight exercise. The beginning posture in this motion is holding the dumbbell at sides of a human trunk, rotating forearm about axis z_3, and keeping the motion on a plane paralleling mid sagittal plane. In the kinematic model, the angles of θ_2 and θ_3 are fixed on 90 and 0 degrees respectively, and the forearm rotates about axis z_3 with θ_4. Substituting the angles of θ_2 and θ_3 into the Eqns. (11)-(13) yields the joint torque of θ_2 as zero, while the joint torques of θ_3 and θ_4 are equalized and expresses as

$$\tau_{dc,3} = \tau_{dc,4} = [m_f g(r_{EF} - r_{f,x}) + m_w g r_{EF}] s\theta_4 \quad (38)$$

In elbow flexion-extension motion with upper limb exoskeleton, the motions of upper arm and forearm are same as dumbbell curl motion. Substituting the angles, θ_2 and θ_3, on dumbbell curl motion into the Eqns. (22)-(24), the joint torques of elbow joint with upper limb exoskeleton are obtained. The joint torque of θ_2 same as shoulder flexion-extension motion is expressed as Eqn. (31), while the joint torques of θ_3 and θ_4 are shown as

$$\tau_{exo,dc,3} = [m_f g(r_{EF} - r_{f,x}) - m_4 g(r_{4,x} - r_{EF}) + K_2 l_{EA_2} l_{SF} + K_3 l_{EA_3} l_{SC}] s\theta_4 \quad (39)$$

$$\tau_{exo,dc,4} = [m_f g(r_{EF} - r_{f,x}) - m_4 g(r_{4,x} - r_{EF}) + K_2 l_{EA_2} l_{SF} + K_3 l_{EA_3} l_{SC} - K_2 l_{EA_2} r_{SE} + K_3 l_{EA_3} r_{SE}] s\theta_4 \quad (40)$$

The spring design condition of spring K_3 is same as frontal raise motion and shown as Eqn. (28). The joint torques of θ_3 and θ_4 in the upper limb exoskeleton have to be equal to dumbbell curl motion, and the coefficients of $s\theta_4$ in Eqn. (38) must equal Eqns. (39) and (40). The design conditions of spring K_2 and K_3 are obtained as

$$K_2 l_{EA_2} = K_3 l_{EA_3} \quad (41)$$

$$l_{SF} = 0 \quad (42)$$

$$l_{SC} = \frac{m_w g r_{EF} + m_4 g(r_{4,x} - r_{EF})}{K_3 l_{EA_3}} \quad (43)$$

On dumbbell curl motion, the increase of resistance is through increasing the weight of external load, m_w. The adjustment of spring K_3, i.e., l_{SC}, can be used to increase resistant force from Eqn. (43).

For strengthening triceps, there is overhead triceps extension in free-weight exercise. In exercise with upper limb exoskeleton, the motion can be performed by elbow flexion-extension as well. The beginning posture of overhead triceps extensions is holding upper limb with dumbbells at sides of ear, then rotating forearm to the back of the body about axis z_3, and keeping the motion on a plane paralleling mid sagittal plane. In the kinematic model, the angles of θ_2 and θ_3 are fixed on 90 and 180 degrees respectively, and the forearm rotates about axis z_3 with θ_4. Substituting the angles of θ_2 and θ_3 into the Eqns. (11)-(13) and (22)-(24), and the momentums of free-weight exercise have to be same as the upper limb exoskeleton. Therefore, the design condition of spring K_2 and K_3, same as the elbow flexion-extension exercise for training biceps, are shown as Eqns. (41)-(43). In elbow flexion-extension exercise for training biceps and triceps, the installation of spring K_1 can be set on any position for it will not affect the results of muscle strengthening.

5 EVALUATION OF THE UPPER LIMB EXOSKELETON

5.1 Anthropometric Parameters of the Upper Limb

Detailed design of the upper limb exoskeleton depends on the anthropometric parameters associated with the user's upper limb. The link length r_{SE} and r_{EF} of the upper arm and the forearm can be measured via access to many database of anthropometry in the world. According to the anthropometry resource from NASA, the research of Clauser et. al., and the institute of occupational safety & health in Taiwan [23-25], the link length of upper arm and forearm for the small, the mid, and the large sized human beings are listed in Tab. 2.

The upper limb exoskeleton for muscular exercises is designed by four links and four zero-free-length springs in which the springs provide not only resistant force for exercise but balance of the weight of links. Also, the masses of links would generate the shoulder and elbow joint torques. Hence, it is important to consider the mass properties of each link when designing the spring adjustable points location. The masses and corresponding coordinates of the mass centers of each link are listed in Tab. 3.

For detailed designing the spring attachments of the upper limb exoskeleton, interference among different links during exercise needs to be considered. For example, the attached point A_3 of spring K_3 and link 4 is in a prominent link on link 4 that exceeds elbow joint. In the upper limb stretching course, motion interference of link 4 and link 2 would happen if the length of prominent link is longer than upper arm. Therefore, l_{EA3} is designed as 150mm which is shorter than the length of upper arm. On the other hand, the length of attached point of spring K_1 together with link 1 $l_{S'A1}$ is designed as 100mm. In muscular exercise, the upper limb exoskeleton increases the resistance by adjusting the length l_{SL}, l_{SF}, and l_{SC} between attached points of springs K_1, K_2 or K_3 and link 2, respectively. In this study, the maximum resistant force of the upper limb exoskeleton is designed on 7 kg, and the spring adjustable points are limited in the range of 40mm to 120mm for individuals. The spring K_4 that connects the link 1 and 2 balances the weight of link 2, 3, and 4, while the adjustable length $l_{S'B}$ is limited in the range of 15mm to 50mm.

Substituting the limits of spring adjustable length, 40mm to 120mm, the maximum resistance 7kg, and the mass properties of linkages along with anthropometric parameters of humans to Eqn. (27), the range of spring stiffness of K_1 can be obtained as

$$2.666\ N/mm \le K_1 \le 6.027\ N/mm \tag{44}$$

Following the same steps, in shoulder flexion-extension exercise, the range of spring stiffness of K_2 can be derived from Eqn. (37), and in elbow flexion-extension exercise, the range of spring stiffness of K_3 are obtained from Eqn. (43).

$$0.539\ N/mm \le K_2 \le 1.627\ N/mm \tag{45}$$

$$1.323\ N/mm \le K_3 \le 2.901\ N/mm \tag{46}$$

In practice, designing constant spring stiffness of these four zero-free-length springs are 5.449N/mm, 1.058N/mm, 1.411N/mm and 0.774N/mm respectively. The spring design conditions of exoskeleton are functions of the lengths of upper arm and forearm and mass properties of links. Utilizing the values of r_{SE}, r_{EF}, K_1, K_2 , K_3 and K_4 along with the parameters of links given in Tab. 3, the range of spring adjustable points

Table 2 ANTHROPOMETRIC PARAMETERS OF UPPER LIMB

Dimension descriptions	Small	Mid	Large
Upper arm (r_{SE} ,mm)	224	255	286
Forearm (r_{EF} ,mm)	267	317	368

Table 3 MASS PROPERTIES OF THE DESIGN

Links	Mass(kg)	r_x (mm)	r_y (mm)	r_z (mm)
1	0.407	-45	82	26
2	0.834	-13	29	-32
3	0.049	143	0	-92
4	0.544	94	0	-102

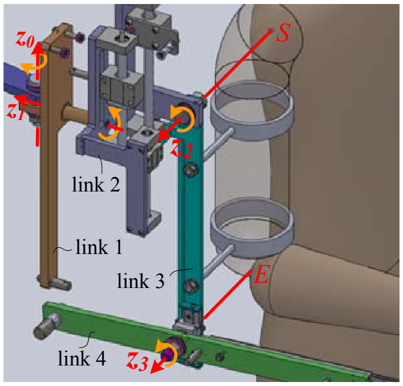
Table 4 DETAILED DESIGN CONDITIONS OF SPRINGS

	Spring design conditions (mm)			
	Adjustments of springs	Small	Mid	Large
Shoulder abd/add exercise	$l_{S'L}$	5/60		
	$l_{S'A1}$	100		
Shoulder flx/ext exercise	l_{SF}	6/60		
	l_{EA2}	267	317	368
	l_{SC}	0		
	l_{EA3}	0		
Elbow flx/ext exercise	l_{SF}	0		
	l_{EA2}	188		
	l_{SC}	9/120		
	l_{EA3}	150		
All exercise	$l_{S'B}$	11		

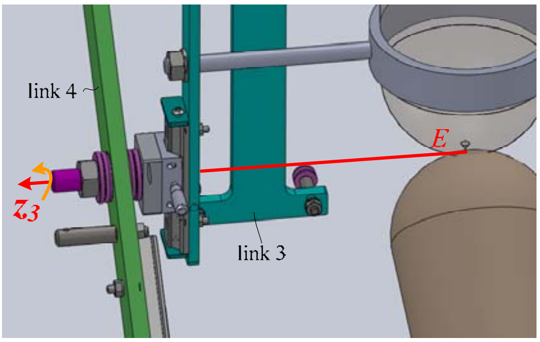
can be immediately obtained from Eqns. (28)-(29), (35)-(38) and (42)-(44) and listing in Tab. 4. One thing should be noted that, in Tab. 4, the two values of an installing length separated by a slash correspond to the two resistant forces of 1 and 7 kg. Meanwhile, $l_{S'B}$ is fixed in either exercise with the value of 31.4 mm. In shoulder flexion-extension, the spring K_3 provides the balance of the weight of link 3 and link 4, but the effect is rather small; therefore, l_{SC} can be regarded as zero in this exercise.

In embodiment design of the device, the arrangement of three revolute joints for 3-DOF shoulder joint is illustrated in Fig. 4(a). The revolute joints of axes z_0 and z_2 are achieved by thrust bearings for decreasing the defects of clearance. And the revolute joint of axis z_1 is carried out by a ball bearing. The elbow joint is effected by a revolute joint mounted on a slide, through the slide guide to adjust the length of upper limb for fitting in with different subjects and using thrust bearings to achieve elbow flexion-extension motion. The CAD drawing is shown in Fig. 4(b).

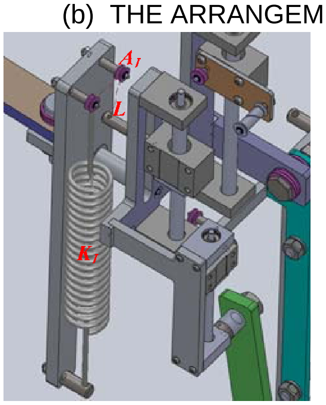
In this design, a standard spring with wire and pulley construction is used to emulate a zero-free-length spring. The zero-free-length spring K_1 is attached to point A_1 on link1 and point L on link 2. An embodiment design of spring K_1 is illustrated in Fig. 4(c), the standard spring K_1 is fixed in a pin and connected the point A_1 and point L by wire and pulleys. The distance of point A_1 to L is not limited to the free-length of spring. The arrangements of K_2 and K_3 springs are same as spring K_1 and shown in Fig. 4(d). For increasing the intensity of exercise, adjust the installation in link 2. Possibility of the



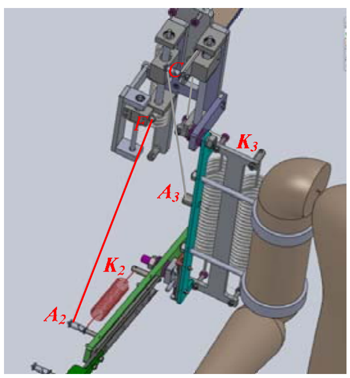
(a) THE ARRANGEMENT OF SHOULDER JOINT



(b) THE ARRANGEMENT OF ELBOW JOINT



(c) THE ARRANGEMENT OF SPRING K_1



(d) THE ARRANGEMENT OF SPRINGS K_2 AND K_3

Figure 4 EMBODIMENT DESIGN OF UPPER LIMB EXOSKELETON

interference between links and springs during exercise is considered and eliminated.

5.2 Muscular Exercises

A series of experiments are conducted to measure the joint torques of shoulder abd-add, flx-ext, and elbow flx-ext exercise. In this study, the joint torques of dumbbell exercise are carried out by two healthy subjects (male and female), the total body weight (TBW) of the male and female subjects are 70 kg and 55 kg, respectively. The length of upper arm and forearm of the male are 275mm and 320mm, and the female 240mm and 270mm. In experiments of shoulder abd-add, shoulder flx-ext and elbow flx-ext exercises, the resistant force are 4lb and 8lb weight dumbbells, and the experimental

Table 5 THE ADJUSTABLE LENGTH OF SPRINGS FOR 4 AND 8 POUNDS WEIGHT RESISTANCE OF THE TWO SUBJECTS

Muscular exercises	Adjustments of springs (mm)	Male	Female
Shoulder abd/add exercise	$l_{S'L}$	11/26	9/22
Shoulder flx/ext exercise	l_{SF}	13/30	14/30
Elbow flx/ext exercise	l_{SC}	21/48	18/39
All exercises	$l_{S'B}$	11	

torques are regarded as the objective joint torques of the design. According to the anthropometric parameters of upper limb of the two subjects and the parameters of links given in Tab. 3, the design spring conditions of the upper arm exoskeleton can be obtained as Tab. 4, while the exact values of $l_{S'L}$, l_{SF}, l_{SC} for 4lb (1.8kg) and 8lb (3.6kg) weight resistances are listed in Tab. 5. Utilizing these parameters to build a kinematic model of the upper limb along with the design in the computer simulation software ADAMS helps to simulate the demonstration of the achievement of this design.

Based on the experiments of three types of exercise, the upper limb moves from the initial configuration where the upper arm and forearm is in vertical position, and ends in the same position. The measurements of joint torques are achieved by Biodex III isokinetic dynamometer. The Biodex System III isokinetic dynamometer (Biodex Medical Systems, Shirley, New York, USA) [26, 27] is an isokinetic dynamometer with an electrically controlled servomechanism commonly used in clinical and research settings. For shoulder abduction-adduction exercise, the movement of the upper limb is driven by shoulder joint about axis z_1; the joint angle in θ_2 ranges from 90 degree to 180 degree, and then reverses the motion from 180 degree to 90 degree to complete the whole motion. The movement of the upper limb for shoulder flexion-extension exercise is driven by shoulder joint about axis z_2; the joint angle in θ_3 ranges from 0 degree to 90 degree and then returns back to the beginning position of the motion. The period of both two shoulder exercise is 10 seconds. In elbow flexion-extension exercise, the movement of the forearm is driven by the elbow joint about axis z_3, and the period of the motion is 15.6 seconds. The joint angle in θ_4 ranges from 0 degree to 150 degree on the first half period and changes back to 0 degree. The plot of joint angles of each exercise versus time is shown in Fig. 5.

Figures 6 show the values of shoulder and elbow joint torques of dumbbell exercise and the exoskeleton. The black solid line is the joint torque of shoulder abd-add, flx-ext, and elbow flx-ext exercise from the experiment of exercise with 4lb weight dumbbell. The red solid line is the joint torque of 4lb weight resistance from the upper limb exoskeleton simulated through ADAMS. The dash line represents the resistance is 8lb weight.

5.3 Results and Discussion

The angular velocity of simulation in ADAMS software is set constant, but in the experiment, the constant angular velocity is difficult to maintain and might cause the position of peak moments to slightly deflect. This state is obvious in elbow flexion-extension motion. In Fig. 6(a) and Fig.6(b), for the shoulder abduction-adduction exercise, the average

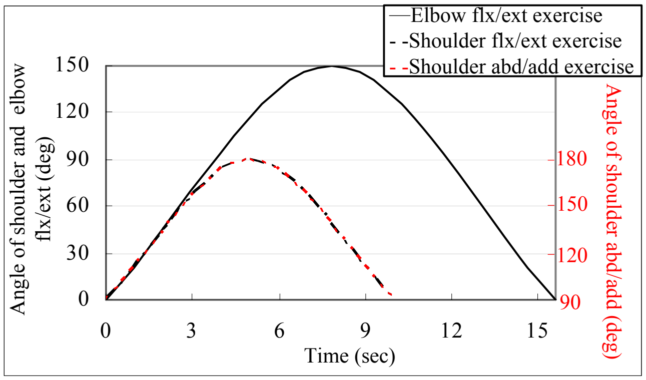
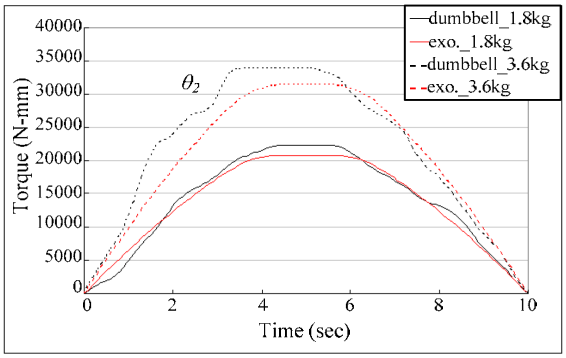
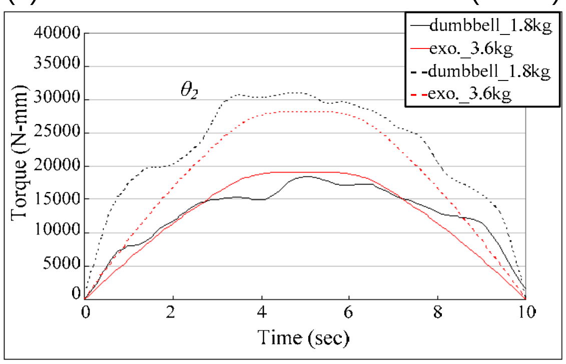


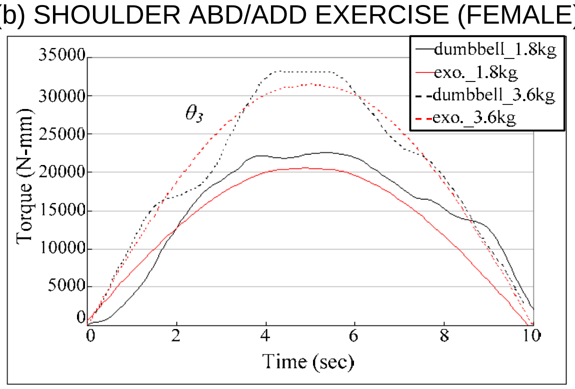
Figure 5. THE JOINT ANGLES OF UPPER LIMB.



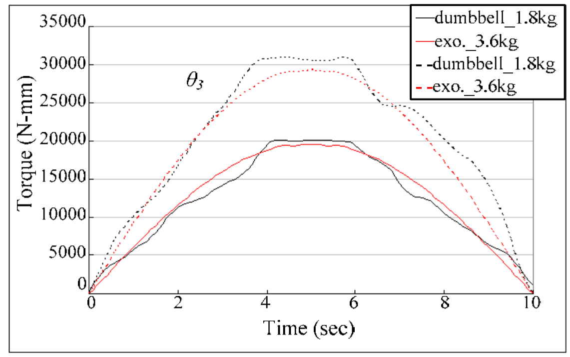
(a) SHOULDER ABD/ADD EXERCISE (MALE)



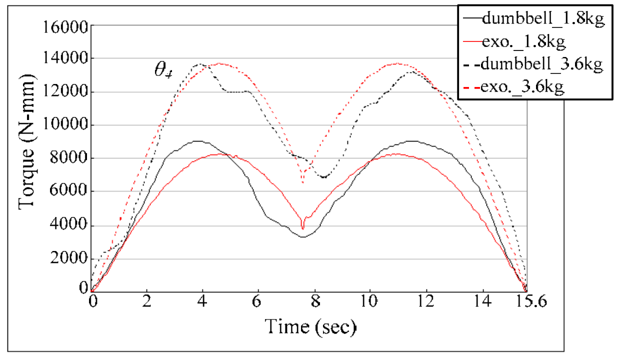
(b) SHOULDER ABD/ADD EXERCISE (FEMALE)



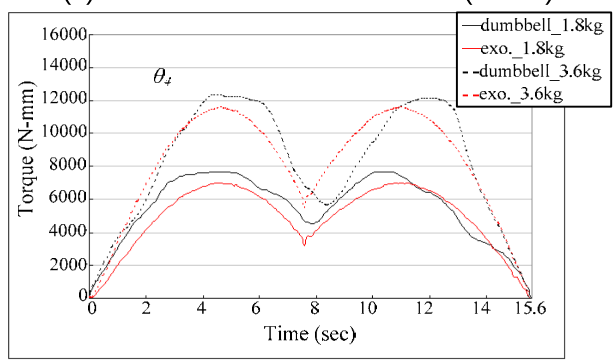
(c) SHOULDER FLX/EXT EXERCISE (MALE)



(d) SHOULDER FLX/EXT EXERCISE (FEMALE)



(e) ELBOW FLX/EXT EXERCISE (MALE)



(f) ELBOW FLX/EXT EXERCISE (FEMALE)

Figure 6 COMPARISONS OF EXPERIMENT AND SIMULATION

difference of peak moments between experimental data and simulated data is about 6.49%. In Fig. 6(c) and Fig. 6(d), for shoulder flexion-extension exercise, the difference of peak moments between varied resistant force and subjects is quite small, about 5%. For elbow flexion-extension exercise in Fig. 6(e) and Fig. 6(f), the average difference of peak joint torques between experiment data and simulated data is about 6.73%. The tendency of joint torque curves is similar and the differences between experimental data and simulation data of the upper limb exoskeleton are about 6% in three types of exercise. The results prove that the design matches with the objective free-weight exercise model.

6 CONCLUSIONS

In this study an upper limb exoskeleton design for free-weight exercise to strengthen the principal muscles of upper limb and shoulder is presented. The resistant force is provided by spring elements through the adjustment of the spring attachment points to increase the intensity of muscular exercise. The upper limb exoskeleton can perform shoulder abduction-adduction, flexion-extension, and elbow flexion-extension exercise, and the joint torques of shoulder and elbow with the exoskeleton have to be equal to the objective joint torques obtained from a model of free-weight exercise.

Free-weight exercise model can strengthen principal muscles of upper limb and shoulder by dumbbell lateral raise, dumbbell frontal raise, dumbbell curl motion and overhead triceps extension. According to anthropometric parameters, this study provides the spring design conditions of three exercise for the small, the mid, and the large sized human beings. The comparisons with the measurements of joint torques by Biodex III for a male and a female adult and ADAMS prove that the design matches with the objective free-weight exercise model. With the arrangement of small-inertia springs, the design is capable of preventing the muscles from injuries caused by the huge inertia change.

Detailed design of the upper limb exoskeleton is undergoing, a prototype will be built for further evaluations once the detailed design refinement is completed and fully reviewed.

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