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具上肢特定肌肉強化與傷害防護訓練機的設計與評估

An upper limb exoskeleton for pinpointed muscular exercises with overextension injury prevention

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中文摘要

肌肉組織是否強健會直接影響日常生活機能，應適當的予以鍛鍊，防止肌力逐漸衰弱，透過阻力運動(resistance exercise)可增強肌肉的強度與耐久力。本論文提出一個具有上肢特定肌肉強化與傷害防護訓練機的設計，不僅可提供健康的使用者作肌肉強度的訓練且可幫助肌肉能力退化的病患回復其肌肉的能力。常見之肌力訓練機器只允許單一平面運動但其訓練到的肌肉有限，反觀具有多自由度的自由重量運動(如啞鈴運動)則對整體肌肉強度的改善較為均勻。本文提出的設計在肩膀關節部份可提供三個自由度的運動且允許手肘關節一個自由度的運動，分別可作肩膀內旋-外旋(internal-external)、外展-內縮(abduction-adduction)與屈曲-伸展(flexion-extension)、再加上手肘屈曲-伸展運動。本文藉由建構一個自由重量運動之模型而得到在運動過程中人體上肢關節所受到的力矩值作為此設計的目標力矩值。此訓練機則是藉由三條彈簧的彈力來提供運動所需的阻力，使用者利用此訓練機進行運動時其關節所受到的力矩值必須相等於自由重量運動，進而達到相同的訓練效果。相較於自由重量運動是透過一個外加荷重提供運動所需之阻力，此設計之阻力值的增加則是藉由手動調整其彈簧的接點位置來達成，且其調整量與外加荷重呈現線性關係，可減少在啞鈴運動中高阻力時因過大的慣性力而導致關節過度伸展。本文提出之訓練機可模擬自由重量運動裡的啞鈴彎舉、前舉、側舉以及頭頂三頭肌延伸運動藉以訓練手臂上二頭肌、三頭肌、三角肌等手臂主要作用肌群，且藉由訓練機的幫助使手臂在運動過程中維持其正確的運動姿勢。同時，藉由等速肌力量測儀(isokinetic dynamometer)進行實驗量測實際自由重量運動時人體關節受到的力矩值，並與軟體模擬的結果相比，證實此設計的可行性並進行具體化設計。

關鍵詞：阻力運動、上肢、自由重量運動、肌力訓練、彈簧

Abstract

Highly 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 merely isolate specific muscle groups to be trained. Compared with machines, free-weight exercise is a whole-body training in which human limb can move 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 consisted with 3-DOF shoulder joint and 1-DOF elbow joint. The joint torques of shoulder and elbow joints with the upper limb exoskeleton have to be equal to the objective joint torques that obtained 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. Results of experiments which use isokinetic dynamometer to measure joint torques of male and female adult for shoulder abduction-adduction, flexion-extension, and elbow flexion-extension exercise prove the design is feasible. According to the results of preliminary design evaluation, this study provides the embodiment design of the upper limb exoskeleton.

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

Nomenclature

$\boldsymbol{g}$	vector of gravitational acceleration, pointing downwards
K_i	spring stiffness of spring i
$\boldsymbol{l}_{\boldsymbol{A_iB_i}}$	vector of spring i
l_{A_1C}	adjustable length from point S to point A_1
l_{SA_i}	adjustable length from point S to point A_i, i=2, 3
l_{PB_1}	link length form point P to point B_1 on link 1
l_{EB_i}	link length from point B_i on link 4 to elbow joint E, i=2, 3
l_{CP}	link length from point C on link 2 to point P
m_f	mass of forearm
m_i	mass of link i
m_u	mass of upper arm
m_w	mass of external load
$\boldsymbol{r_{EH}}$	vector of forearm which from elbow joint E to middle of hand H
$\boldsymbol{r_{SE}}$	vector of upper arm which from shoulder joint S to elbow joint E
$\boldsymbol{r_f}$	vector of mass center of forearm referenced on CS 4
$\boldsymbol{r_i}$	vector of mass center of link i referenced on CS i
$\boldsymbol{r_u}$	vector of mass center of upper arm referenced on CS 3
${}^{i-1}T_i$	D-H transformation matrix between link i and $i-1$
V_{total}	total potential energy of the upper limb exoskeleton
V_g	gravitational potential energy of free-weight exercise
$V_{L\,i}$	gravitational potential energy of link i

$V_{S\,i}$	elastic potential energy of spring i
M_i	joint torque of axis-z_i which exercise with exoskeleton
$M_{i,dc}$	joint torque of axis-z_i which exercise with exoskeleton to emulate dumbbell curl motion
$M_{i,fr}$	joint torque of axis-z_i which exercise with exoskeleton to emulate frontal raise motion
$M_{i,lr}$	joint torque of axis-z_i which exercise with exoskeleton to emulate lateral raise motion
$M_{i,tri}$	joint torque of axis-z_i which exercise with exoskeleton to emulate overhead triceps extension
θ_i	angle rotates about axis-z_i
τ_i	joint torque of axis-z_i of objective free-weight exercise
$\tau_{i,dc}$	joint torque of axis-z_i of dumbbell curl motion
$\tau_{i,fr}$	joint torque of axis-z_i of frontal raise motion
$\tau_{i,lr}$	joint torque of axis-z_i of lateral raise motion
$\tau_{i,tri}$	joint torque of axis-z_i of overhead triceps extension

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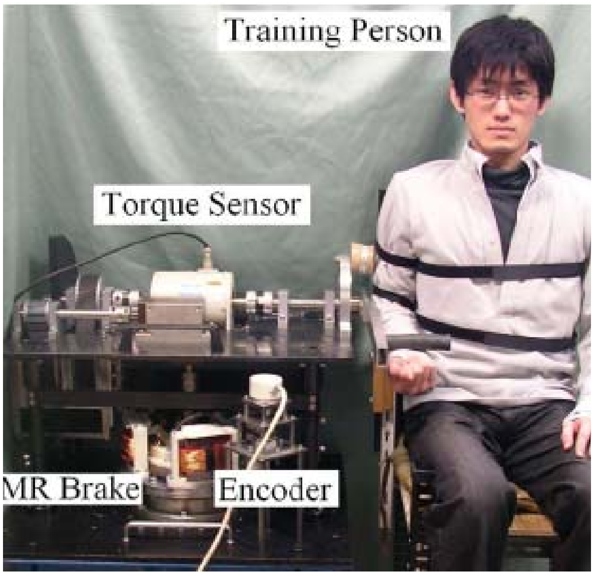
CHAPTER 1

Introduction

Hisamoto and Higuchi [1] 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. The reason is that more highly automated equipments in the recent daily life reduce the opportunities for muscle using. However, 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, 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]. More resistance exercise machines have been developed for rehabilitation function. For example, Dobbe et al. [29] have demonstrated a finger tendon rehabilitation device for isotonic exercise by a leaf spring. Dong et al. [30] have proposed an exercise machine which provided isokinetic and isometric exercises by magnetorheological fluids for strengthening the muscle of lower limb.

Isometric exercise is a training in which the muscle can be contracted without moving joints. The exercise is performed beyond the maximum strength of an individual to resist an immovable object such as a wall, a free-weight, or an exercise machine loaded. Most studies indicated isometric exercise is superior to isokinetic exercise and isotonic exercise in muscle strength gains [6, 7]. However, isometric exercise does not improve motor performance ability; the recovery of muscles' dynamic functions must be through dynamic resistance exercise. Isokinetic exercise is a training in which the muscle contracts at a constant angular velocity of joint [5]. The velocity control mechanism is usually an electronic dynamometer or a hydraulic valve. Thistle et al. (1967) presented the isokinetic exercise by a precise control of velocity movement. Kikuchi et al. [9] developed an isokinetic exercise system by using MR fluid brake, and Garner [10] designed a four-bar linkage exercise machine with hydraulic resistance to be close to isokinetic exercise. 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]. Most studies have demonstrated the exercise which combines concentric and eccentric contraction can obtain greater gains in muscle strength [5, 31, 32].

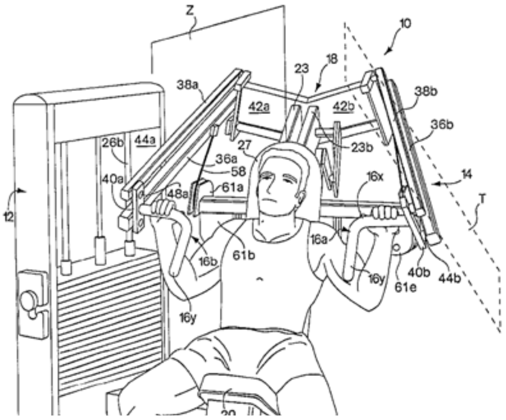
(a) Isometric exercise: push against an immoveable object [35]



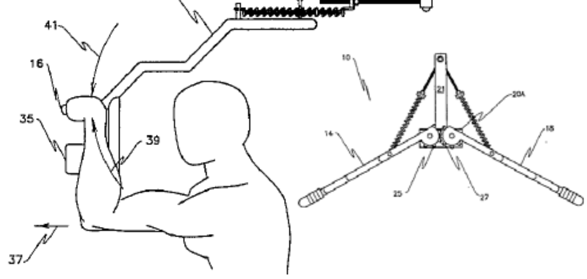
(b) Isokinetic exercise system [9]

Fig. 1 Illustrations of isometric and isokinetic exercise machines

Isotonic exercise is a training where the external resistance does not vary during the training [5]. This exercise has concentric and eccentric muscle contraction throughout the range of motion. It is superior to the isokinetic exercise in gains of muscle strength [11]; therefore, isotonic exercise was chosen to strengthen the muscle force in this study. Examples of isotonic exercise are free-weight exercise which uses dumbbells as the external resistance, and the idea of using machines instead of free-weights to provide resistance is then developed. An example of machines-assisted exercise in early years is found in U.S. patents for an exercising chair by White [12], which strengthens the muscles of arm and chest through resisting the resistance of spring and weight of the exerciser. Most machines use weight stack as the source of resistance, e.g., U.S.4836535 [13], U.S.5336148 [14], and U.S.6152864 [15]. Some machines use spring as the source of resistance, e.g., U.S.5613928 [16] and U.S.7060012 [17]. The machines constrain the movement of weight stack to vertical positions by a fixed guidable frame and the movement of human body. It requires less skill to control the weight stack than free weight and reduces the possibilities of injury. However, most machines permit movements in a single plane to isolate specific muscle groups to train rather than free-weight exercises which human limb with external weights can move on different planes for training more muscle groups [2, 18, 19]. It is because explosive movements are not encouraged in free-weight exercise and weight-stack machines. During muscular exercise, the muscles need more force to overcome the inertia of heavier weights during ballistic movements, and the inertial force would increase dramatically when the free-weights are being stopped in a short time.



(a) Incline press apparatus for exercising [15]



(b) Jointed bar [16]

Fig. 2 Illustrations of isotonic exercise machines

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; the upper arm can perform the motions of internal-external(int-ext), abduction-adduction(abd-add), and flexion-extension(flx-ext), and the forearm is able to carry out flexion-extension motion. The joint torques of shoulder and elbow joints with the upper limb exoskeleton have to be equal to 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 locations of springs need to be adjusted for higher intensity training, and the gravitational potential energies including upper limb and exoskeleton would remain constant unlike free-weight exercise that increases external weights to induce huge inertia in heavier muscle strengthening; hence, the exoskeleton is capable of preventing the muscle from injuries caused by the huge inertia change. The upper limb exoskeleton can be applied in muscle strengthening or muscle strength recovery, with the advantages of compact design and small footprint make it very suitable for people or patients doing exercise or rehabilitation at home.

CHAPTER 2

Kinematic model and joint torque analysis

2.1 Kinematic model of upper limb

An upper limb contains the upper arm and the forearm. The upper arm in Fig. 3 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 H. The segmental length of the upper arm and forearm is r_{SE} and r_{EH}, respectively. The hand is usually at its neutral position in the forearm movements; therefore, the gravitational variation due to the wrist motion is negligible. Hence, the upper limb can be modeled as a two-link linkage. The geometries of the upper arm and the forearm are assumed axially symmetric and the positions of mass centers, M_u and M_f, are assumed to be fixed and located on the center lines with respect to upper arm and forearm; the mass of human hand are ignored here because it is relatively light compared to the upper limb. The kinematic model is shown as in arm linkage in Fig. 1, and the GH joint in human skeleton that connects scapular and humerus is modeled to 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.

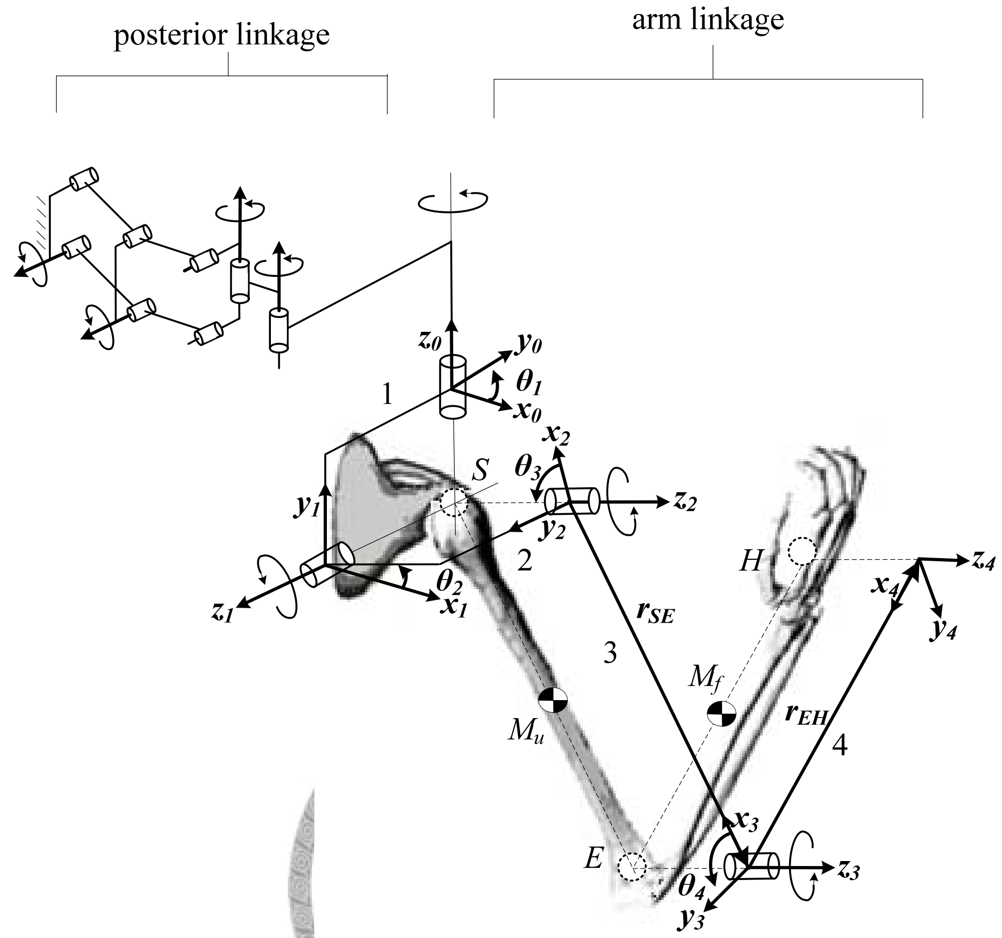


Fig. 3 Kinematic model and coordinate system of right upper limb

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

$$^{i-1}\boldsymbol{T}_i = \begin{bmatrix} \cos\theta_i & -\cos\alpha_i \sin\theta_i & \sin\alpha_i \sin\theta_i & a_i \cos\theta_i \\ \sin\theta_i & \cos\alpha_i \cos\theta_i & -\sin\alpha_i \cos\theta_i & a_i \sin\theta_i \\ 0 & \sin\alpha_i & \cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (1)$$

where d_i is the distance along z_{i-1} from x_i-axis to x_{i-1}-axis and a_i is the distance along x_i from z_i-axis and z_{i-1}-axis; 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}.

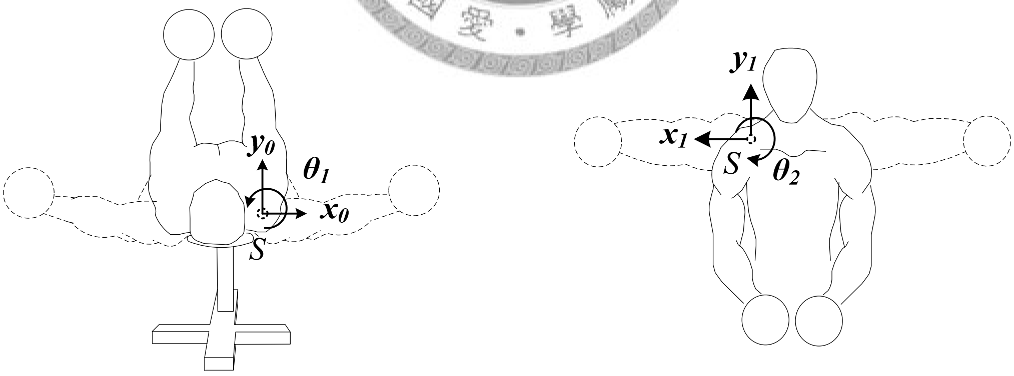
From Fig. 3, the origins of CSs 0, 1 and 2 are coincident at GH joint S, and their corresponding d_i and a_i are zero. The axes z_2 and z_3 are parallel and their distance is length of upper arm, and z_3-axis and z_4-axis are parallel and the distance is length of forearm. And θ_1, θ_2, θ_3 and θ_4 represent the rotation angles about the axes of shoulder int-ext, abd-add, flx-ext and elbow flx-ext exercise, respectively. The D-H parameters are listed in Table 1.

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	$-r_{EH}$	0

The inside portion of human shoulder is called shoulder girdle, which is consisted of clavicle and scapular. The motion of shoulder girdle is enabled by the scapulothoracic, sternoclavicular and acromioclavicular joint. Klopčar et al. [20] indicated the girdle motion can be modeled as two degrees of freedom. The motion of girdle is enabled by two parallelogram linkages and two serially connected links, and the assembly is shown in posterior linkage in Fig. 3. The parallelogram linkages provide the elevation-depression movement of scapular, and the two serially connected links allow the GH center to be free on a horizontal plane.

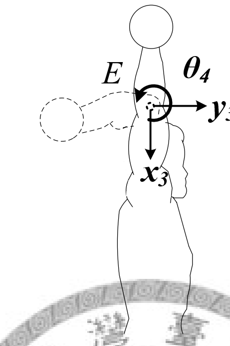
The muscles on the shoulder are complicated. The deltoid muscles are the principal muscle on the shoulder, and they act in most shoulder movements; besides, the rotator cuff act to stabilize the shoulder. In the back of human body, latissimus dorsi has functions about raising of the arm, and there is pectoralis major muscle in the chest of human body. On the upper arm, there are biceps and triceps; the former contributes more when forearm is flexed, and the latter has contribution on elbow extension. In free-weight exercises, dumbbell exercises are commonly used to train muscles of shoulder and upper arm (Fig. 4). In this study, according to degrees of freedom of shoulder, dumbbell bench fly, dumbbell lateral and frontal raise motions are existed corresponding to shoulder int-ext, abd-add, and flx-ext motion, respectively. The dumbbell bench fly is an exercise for strengthening the pectoralis major muscles. The lateral raise motion can strengthen deltoid muscle, suparaspinatus, latissimus dorsi and pectoralis major. The frontal raise motion mainly training deltoid muscle, pectoralis major, and latissimus dorsi. There is dumbbell curl motion around the axis of elbow flx-ext to principally train biceps. For major training triceps, an overhead triceps extension is achieved by rotating the forearm about axis of elbow flx-ext [21, 22].



(a) Dumbbell bench fly

(b) Lateral raise motion

(c) Frontal raise motion (d) Dumbbell curl motion



(e) Overhead triceps extension

Fig. 4 Free-weight exercise

2.2 Static 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; the muscle force would be strengthened by increasing the free-weigh load gradually. In Fig. 5, an objective model is constructed as free-weight exercise with an external load m_w grasped in the middle of palm H 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. During exercising, the gravitational potential energy of the kinematic model can be expressed as

$$\begin{aligned} V_g &= -m_u \boldsymbol{g} \cdot (\boldsymbol{r_{SE}} + \boldsymbol{r_u}) - m_f \boldsymbol{g} \cdot (\boldsymbol{r_{SE}} + \boldsymbol{r_{EH}} + \boldsymbol{r_f}) - m_w \boldsymbol{g} \cdot (\boldsymbol{r_{SE}} + \boldsymbol{r_{EH}}) \\ &= -m_u(-g\boldsymbol{k_0}) \cdot (-r_{SE}\boldsymbol{i_3} + r_{u,x}\boldsymbol{i_3}) - m_f(-g\boldsymbol{k_0}) \cdot (-r_{SE}\boldsymbol{i_3} - r_{EH}\boldsymbol{i_4} + r_{f,x}\boldsymbol{i_4}) \\ &\quad - m_w(-g\boldsymbol{k_0}) \cdot (-r_{SE}\boldsymbol{i_3} - r_{EH}\boldsymbol{i_4}) \end{aligned} \tag{2}$$

where $\boldsymbol{r_u}$ and $\boldsymbol{r_f}$ are the mass center position vectors of m_u and m_f referenced on each corresponding CSs and quantities $r_{u,x}$, $r_{u,y}$, $r_{u,z}$, $r_{f,x}$, $r_{f,y}$, and $r_{f,z}$ are the corresponding local coordinates. Note that, quantities $r_{u.y}$ and $r_{f,y}$ are omitted in Eq. (2). For CS0, quantities $r_{u,z}$ and $r_{f,z}$ are zero. The mass center position of m_w is assumed to be located on point *H*.

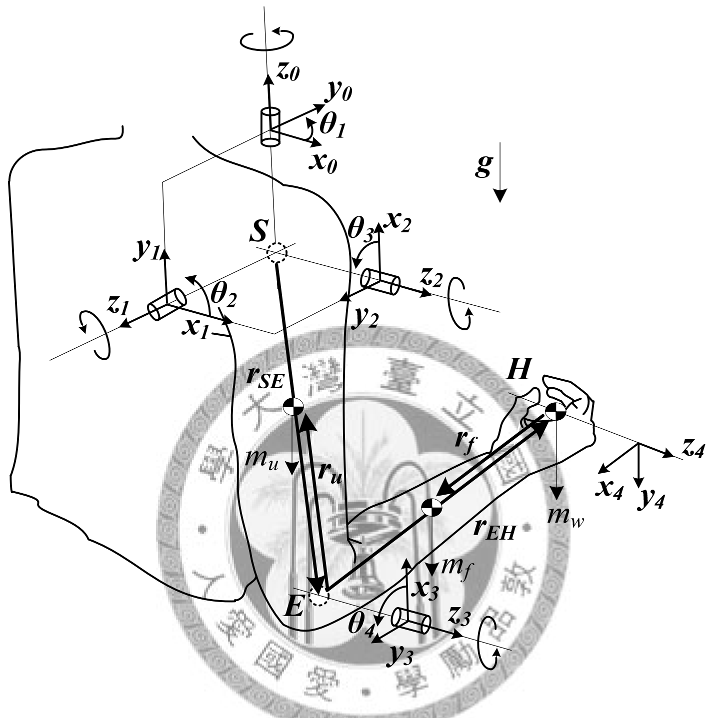


Fig. 5 The objective model of free-weight exercise

Derived from the D-H transformation matrix and parameters on Table 1, for CS 0 with respect to CS 2,

$$\boldsymbol{k_0} = (\sin\theta_2)\boldsymbol{i_2} + (-\cos\theta_2)\boldsymbol{k_2} \tag{3}$$

$$\boldsymbol{k_2} \cdot \boldsymbol{i_3} = 0 \tag{4}$$

$$\boldsymbol{k_2} \cdot \boldsymbol{i_4} = 0 \tag{5}$$

$$\boldsymbol{i_2} \cdot \boldsymbol{i_3} = \cos\theta_3 \tag{6}$$

$$\boldsymbol{i_3} \cdot \boldsymbol{i_4} = \cos\theta_4 \tag{7}$$

$$\boldsymbol{i_2} \cdot \boldsymbol{i_4} = \cos(\theta_3 + \theta_4) \tag{8}$$

Substituting Eqs. (3)-(8) into Eq. (2) yields the following equation for the total gravitational potential energy of the objective model of free-weight exercise

$$\begin{aligned} V_g = & [-m_u g(r_{SE} - r_{u,x}) - (m_f + m_w) g r_{SE}] \sin\theta_2 \cos\theta_3 \\ & - [m_f g(r_{EH} - r_{f,x}) + m_w g r_{EH}] \sin\theta_2 \cos(\theta_3 + \theta_4) \end{aligned} \tag{9}$$

In muscular exercise, external loads provide moments about the pivot joint, there is a tendency for the muscle to resist the opposite torques from external loads; 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 gravitational joint torque τ_i on the joint i can be obtained as

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

Equation (10) suggests that joint torque of θ_1 is zero; the joint torques of θ_2, θ_3 and θ_4 are τ_2, τ_3 and τ_4. The gravitational joint torques of the upper limb can be derived as

$$\begin{aligned} \tau_2 = & [-m_u g(r_{SE} - r_{u,x}) - (m_f + m_w) g r_{SE}] \cos\theta_2 \cos\theta_3 \\ & - [m_f g(r_{EH} - r_{f,x}) + m_w g r_{EH}] \cos\theta_2 \cos(\theta_3 + \theta_4) \end{aligned} \tag{11}$$

$$\begin{aligned} \tau_3 = & [m_u g(r_{SE} - r_{u,x}) + (m_f + m_w) g r_{SE}] \sin\theta_2 \sin\theta_3 \\ & + [m_f g(r_{EH} - r_{f,x}) + m_w g r_{EH}] \sin\theta_2 \sin(\theta_3 + \theta_4) \end{aligned} \tag{12}$$

$$\tau_4 = [m_f g(r_{EH} - r_{f,x}) + m_w g r_{EH}] \sin\theta_2 \sin(\theta_3 + \theta_4) \tag{13}$$

By definition, the moment arm is the perpendicular length from the pivot joint to the line of the acted force, and it would vary with the angel of rotation. The joint torques of shoulder and elbow joints are functions of moment arm and it would change with the rotational angles of upper limb from Eqs. (11)-(13).

CHAPTER 3

Conceptual design of spring-loaded exoskeleton

3.1 Upper limb exoskeleton

In Fig. 3, the upper limb exoskeleton can be separated from arm linkage and posterior linkage; the posterior linkage can be achieved by parallelogram linkages for girdle's motion and shoulder abd-add exercise. In this study, only the arm linkage was taken account in the design.

In practices, the exoskeleton configuration in Fig. 3, link 1 and 2 would interfere with the back side of human body when upper limb rotates outward horizontally. The GH 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, however, this design is difficult to comply with the human GH joint center. Hence, a modified design is proposed on Fig. 6 to avoid such drawbacks, and the exoskeleton is wearable with a band on upper arm and a handle for gripping.

The modified exoskeleton configuration is constructed by four links, and the 4-DOF kinematic chain contains four links where 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*. The axes z_0* and z_1* parallel to axes z_0 and z_1, respectively, and the rotational joint angles of z_0*-axis and z_1*-axis are same as the rotational angles of shoulder int-ext and abd-add exercise, θ_1 and θ_2. Links 2 and 3 are pivoted by a revolute joint of axis z_2 and the rotational joint angle about axis z_2 is θ_3. The interference of link 1 and human body is resolved by parallel shifting the axis of shoulder int-ext and the 3-DOF shoulder joint achieved by the three revolute joints about axes z_0*, z_1* and z_2 which only alignment of z_2-axis and human GH joint center is required. The point P is intersection of axes z_1* and z_2, the moments about point P are same as the human shoulder joint S. For 1-DOF elbow joint, links 3 and 4 are pivoted by a revolute joint of axis z_3 to accomplish the elbow flx-ext exercise. The CSs 0, 1, 2, 3, and 4 are used in the modified exoskeleton configuration, and the relationships between the four CSs are same as previous analysis shown in fig. 3.

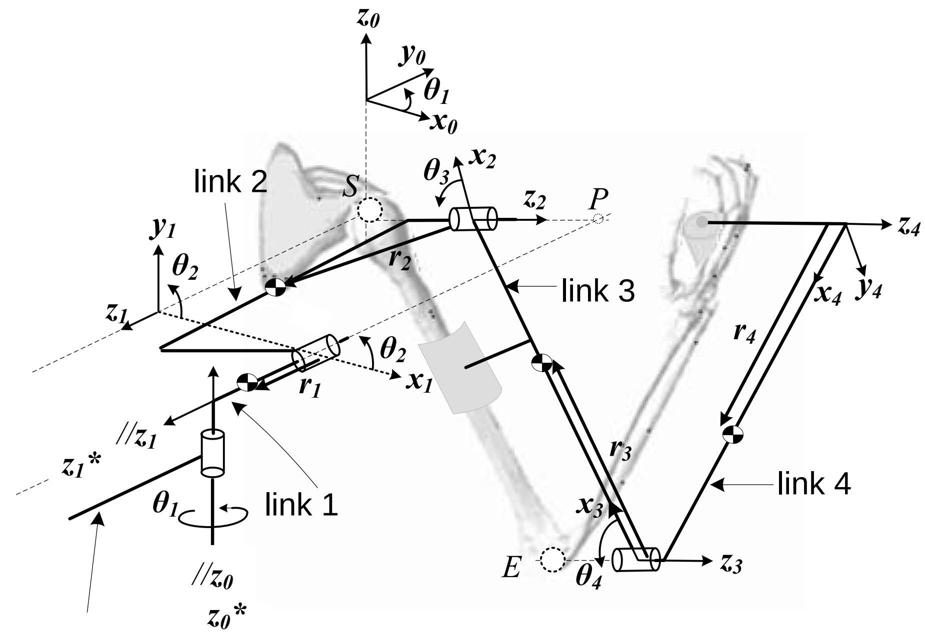


Fig. 6 A modified exoskeleton configuration

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

$$V_{L1} = -m_1 \boldsymbol{g} \cdot \boldsymbol{r_1} = -m_1(-g\boldsymbol{k_0})(r_{1,x}\boldsymbol{i_1} + r_{1,y}\boldsymbol{j_1} + r_{1,z}\boldsymbol{k_1}) = const \tag{14}$$

$$\begin{aligned} V_{L2} &= -m_2 \boldsymbol{g} \cdot \boldsymbol{r_2} = -m_2(-g\boldsymbol{k_0})(r_{2,x}\boldsymbol{i_2} + r_{2,y}\boldsymbol{j_2} + r_{2,z}\boldsymbol{k_2}) \\ &= m_2 g r_{2,x} \sin\theta_2 - m_2 g r_{2,z} \cos\theta_2 + const \end{aligned} \tag{15}$$

$$\begin{aligned} V_{L3} &= -m_3 \boldsymbol{g} \cdot \boldsymbol{r_3} = -m_3(-g\boldsymbol{k_0})(-r_{SE}\boldsymbol{i_3} + r_{3,x}\boldsymbol{i_3} + r_{3,z}\boldsymbol{k_3}) \\ &= m_3 g(r_{3,x} - r_{SE})\sin\theta_2 \cos\theta_3 - m_3 g r_{3,z} \cos\theta_2 + const \end{aligned} \tag{16}$$

$$\begin{aligned} V_{L4} &= -m_4 \boldsymbol{g} \cdot \boldsymbol{r_4} = -m_4(-g\boldsymbol{k_0})(-r_{SE}\boldsymbol{i_3} - r_{EF}\boldsymbol{i_4} + r_{4,x}\boldsymbol{i_4} + r_{4,z}\boldsymbol{k_4}) \\ &= -m_4 g r_{SE} \sin\theta_2 \cos\theta_3 + m_4 g(r_{4,x} - r_{EH})\sin\theta_2 \cos(\theta_3 + \theta_4) \\ &\quad - m_4 g r_{4,z} \cos\theta_2 + const \end{aligned} \tag{17}$$

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

Instead of the external loads, the increase of resistant force on the upper limb exoskeleton is achieved by changing the elastic force of the loaded spring. The resistance would be changed by adjusting the connected locations of spring. On the spring-loaded exoskeleton, spring K_1 is attached to point A_1 on link 2 and point B_1 on link 1; spring K_2 is attached to point A_2 on link 2 and point B_2 on link 4; spring K_3 is attached to point A_3 on link 2 and point B_3 on link 4. The location of connected points A_1, A_2, and A_3 of springs K_1, K_2, and K_3 can be adjusted for more spring resistant force, whereas the points B_1, B_2, and B_3 are fixed connected points.

The concept of employing elastic force as resistance force originated in the reverse idea of gravity-balance mechanism; the zero-free-length spring is used for letting the spring stiffness be independent of the rotational angles of links. Therefore, the resistance force can be changed only by adjusting the connecting locations of springs. The design of zero-free-length springs are adopted in the spring-loaded exoskeleton, which can be accomplished by standard springs combining with cables and pulleys or alignment shafts [33, 34].

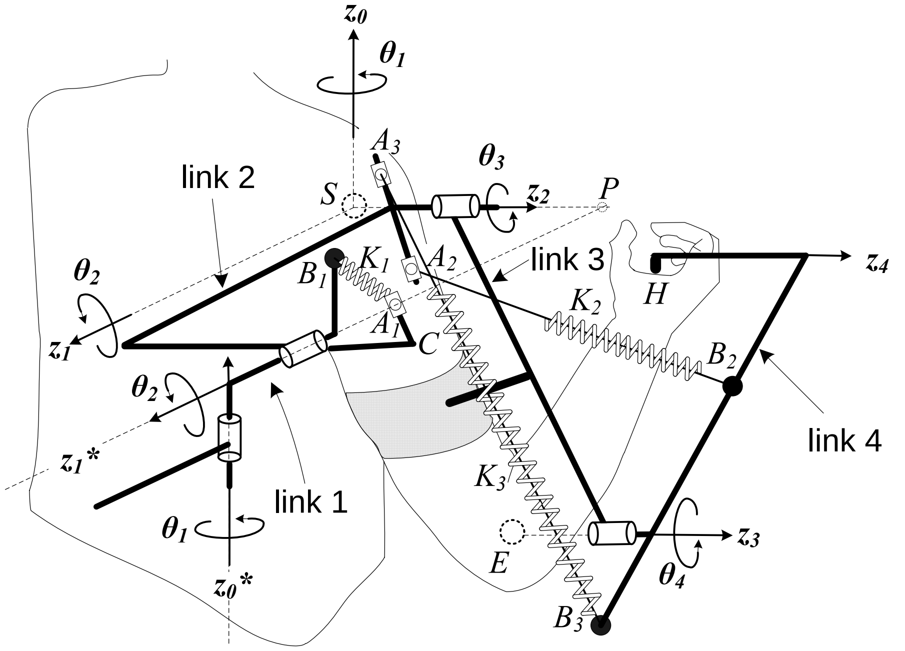


Fig. 7 A schematic diagram of the spring-loaded exoskeleton

The corresponding elastic potential energies, V_{S1}, V_{S2}, and V_{S3} of springs K_1, K_2, and K_3 are then derived as

$$\begin{aligned} V_{S1} &= \frac{1}{2}K_1(\boldsymbol{l_{A_1B_1}} \cdot \boldsymbol{l_{A_1B_1}}) \\ &= \frac{1}{2}K_1(l_{A_1C}\boldsymbol{i_2} + l_{CP}\boldsymbol{k_2} - l_{PB_1}\boldsymbol{k_0}) \cdot (l_{A_1C}\boldsymbol{i_2} + l_{CP}\boldsymbol{k_2} - l_{PB_1}\boldsymbol{k_0}) \\ &= (-K_1 l_{A_1C} l_{PB_1})\sin\theta_2 - (K_1 l_{CP} l_{PB_1})\cos\theta_2 + const \end{aligned} \tag{18}$$

$$\begin{aligned} V_{S2} &= \frac{1}{2}K_2(\boldsymbol{l_{A_2B_2}} \cdot \boldsymbol{l_{A_2B_2}}) \\ &= \frac{1}{2}K_2(l_{SA_2}\boldsymbol{i_2} - r_{SE}\boldsymbol{i_3} - l_{EB_2}\boldsymbol{i_4}) \cdot (l_{SA_2}\boldsymbol{i_2} - r_{SE}\boldsymbol{i_3} - l_{EB_2}\boldsymbol{i_4}) \\ &= (-K_2 l_{SA_2} r_{SE})\cos\theta_3 + (-K_2 l_{EB_2} l_{SA_2})\cos(\theta_3 + \theta_4) \\ &\quad + (K_2 r_{SE} l_{EB_2})\cos\theta_4 + const \end{aligned} \tag{19}$$

$$\begin{aligned} V_{S3} &= \frac{1}{2}K_3\boldsymbol{l_{A_3B_3}} \cdot \boldsymbol{l_{A_3B_3}} \\ &= \frac{1}{2}K_3(l_{SA_3}\boldsymbol{i_2} + r_{SE}\boldsymbol{i_3} - l_{EB_3}\boldsymbol{i_4}) \cdot (l_{SA_3}\boldsymbol{i_2} + r_{SE}\boldsymbol{i_3} - l_{EB_3}\boldsymbol{i_4}) \\ &= (K_3 l_{SA_3} r_{SE})\cos\theta_3 - (K_3 l_{EB_3} l_{SA_3})\cos(\theta_3 + \theta_4) \\ &\quad - (K_3 l_{EB_3} r_{SE})\cos\theta_4 + const \end{aligned} \tag{20}$$

The total potential energy of the upper limb exoskeleton is the gravitational energies of upper limb and the four links together with the elastic potential energies of the three springs and can be expressed as

$$\begin{aligned}
V_{total} &= V_{upperarm} + V_{forearm} + \sum_{i=1}^{3} V_{S\,i} + \sum_{i=1}^{4} V_{L\,i} \\
&= [-m_u g(r_{SE} - r_{u,x}) - m_f g r_{SE} + m_3 g(r_{3,x} - r_{SE}) - m_4 g r_{SE}]\sin\theta_2 \cos\theta_3 \\
&\quad + [-m_f g(r_{EH} - r_{f,x}) + m_4 g(r_{4,x} - r_{EH})]\sin\theta_2 \cos(\theta_3 + \theta_4) \\
&\quad + (-K_2 l_{EB_2} l_{SA_2} - K_3 l_{EB_3} l_{SA_3})\cos(\theta_3 + \theta_4) \\
&\quad + (-K_2 l_{SA_2} r_{GE} + K_3 l_{SA_3} r_{SE})\cos\theta_3 + (K_2 l_{EB_2} r_{SE} - K_3 l_{EB_3} r_{SE})\cos\theta_4 \\
&\quad + (-K_1 l_{A_1C} l_{PB_1} + m_2 g r_{2,x})\sin\theta_2 \\
&\quad - (K_1 l_{CP} l_{PB_1} + m_u g r_{u,z} + m_f g r_{f,z} + m_2 g r_{2,z} + m_3 g r_{3,z} + m_4 g r_{4,z})\cos\theta_2 + const
\end{aligned} \tag{21}$$

Thus, using Eq. (10), the joint torques of θ_2, θ_3 and θ_4 through the use of the exoskeleton are M_2, M_3 and M_4 and can be derived as

$$\begin{aligned}
M_2 &= [-m_u g(r_{SE} - r_{u,x}) - m_f g r_{SE} + m_3 g(r_{3,x} - r_{SE}) - m_4 g r_{SE}]\cos\theta_2 \cos\theta_3 \\
&\quad + [-m_f g(r_{EH} - r_{f,x}) + m_4 g(r_{4,x} - r_{EH})]\cos\theta_2 \cos(\theta_3 + \theta_4) \\
&\quad + [-K_1 l_{A_1C} l_{PB_1} + m_2 g r_{2,x}]\cos\theta_2 \\
&\quad + [K_1 l_{CP} l_{PB_1} + m_u g r_{u,z} + m_f g r_{f,z} + m_2 g r_{2,z} + m_3 g r_{3,z} + m_4 g r_{4,z}]\sin\theta_2
\end{aligned} \tag{22}$$

$$\begin{aligned}
M_3 &= [m_u g(r_{GE} - r_{u,x}) + m_f g r_{GE} - m_3 g(r_{3,x} - r_{GE}) + m_4 g r_{GE}]\sin\theta_2 \sin\theta_3 \\
&\quad + [m_f g(r_{EH} - r_{f,x}) - m_4 g(r_{4,x} - r_{EH})]\sin\theta_2 \sin(\theta_3 + \theta_4) \\
&\quad + [K_2 l_{SA_2} r_{GE} - K_3 l_{SA_3} r_{GE}]\sin\theta_3 \\
&\quad + [K_2 l_{EB_2} l_{SA_2} + K_3 l_{EB_3} l_{SA_3}]\sin(\theta_3 + \theta_4)
\end{aligned} \tag{23}$$

$$\begin{aligned}
M_4 &= [m_f g(r_{EH} - r_{f,x}) - m_4 g(r_{4,x} - r_{EH})]\sin\theta_2 \sin(\theta_3 + \theta_4) \\
&\quad + [K_2 l_{EB_2} l_{SA_2} + K_3 l_{EB_3} l_{SA_3}]\sin(\theta_3 + \theta_4) - [K_2 l_{EB_2} r_{GE} - K_3 l_{EB_3} r_{GE}]\sin\theta_4
\end{aligned} \tag{24}$$

3.2 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 int-ext, abd-add and flx-ext, 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 int-ext 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 int-ext is zero. Therefore, only dumbbell lateral and frontal raise motions about shoulder abd-add and flx-ext exercise for shoulder joint in the upper limb exoskeleton have been taken into account.

3.2.1 Deltoid muscle training from shoulder abduction/adduction

For shoulder abd-add exercise, lateral raise motion is used for strengthening deltoid muscle principally. In the kinematic model, the angles of θ_3 and θ_4 are fixed on 0 degree, the upper arm and forearm can be considered as one link and the rotational is about axis z_1 with θ_2 only. Substituting the 0 degree condition of angles θ_3 and θ_4 into Eqs. (11)-(13), the joint torques of θ_3 and θ_4 equal to zero, and the joint torque of θ_2 can be expressed as

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

In Fig. 7, spring K_1 connects link 1 and link 2 to generate torques about axis of shoulder abd-add. In this exercise with the upper limb exoskeleton, the upper limb maintains the same posture as lateral raise motion with exoskeleton; however, the resistance from external load is replaced by springs. The joint torques of shoulder with exoskeleton are obtained by substituting the same angles as lateral raise motion, θ_3 and θ_4, into Eqs. (22)-(24), the joint torques of θ_3 and θ_4 are zero which are same as lateral raise motion, and the joint torque of θ_2 is shown as

$$\begin{aligned} M_{2,lr} = {} & [-m_u g(r_{SE} - r_{u,x}) - m_f g(r_{SE} + r_{EH} - r_{f,x}) + m_2 g r_{2,x} + m_3 g(r_{3,x} - r_{SE}) \\ & + m_4 g(r_{4,x} - r_{EH} - r_{SE}) - K_1 l_{A_1C} l_{PB_1}]\cos\theta_2 \\ & + [K_1 l_{CP} l_{PB_1} + m_u g r_{u,z} + m_f g r_{f,z} + m_2 g r_{2,z} + m_3 g r_{3,z} + m_4 g r_{4,z}]\sin\theta_2 \end{aligned} \tag{26}$$

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 *cos* θ_2 in Eq. (25) must be equal to Eq. (26), and the coefficients *sin* θ_2 of Eq. (26) is zero. The design condition of spring K_1 obtained from the equation of coefficients of

$cos\ \theta_2$ is expressed as

$$l_{A_1C} = m_w[\frac{g(r_{SE} + r_{EH})}{K_1 l_{PB_1}}] + \frac{m_2 g r_{2,x} + m_3 g(r_{3,x} - r_{SE}) + m_4 g(r_{4,x} - r_{EH} - r_{SE})}{K_1 l_{PB_1}} \qquad (27)$$

Equation (27) represents linear proportion relationship between the weight of external load m_w and the length of connected points of spring K_1 with the only adjustment of l_{A_1C} to increase the resistance for training intensity.

The weights of upper limb and exoskeleton generate momentum about axis z_1* due to the effect of gravity, and the spring K_1 can also compensate the gravitational potential energy of upper limb and links. The spring design condition of spring K_1 is expressed as

$$l_{CP} = -\frac{m_u g r_{u,z} + m_f g r_{f,z} + m_2 g r_{2,z} + m_3 g r_{3,z} + m_4 g r_{4,z}}{K_1 l_{PB_1}} \qquad (28)$$

3.2.2 Deltoid muscle training from shoulder flexion/extension

In free-weight exercise, frontal raise motion is greatly adopted for training deltoid muscles about axis of shoulder flx-ext. 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. By substituting the conditions of θ_2 and θ_4 into Eqs. (11)-(13), the joint torque of θ_2 equals to zero, and the joint torques of θ_3 and θ_4 can be expressed as

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

$$\tau_{4,fr} = (m_f g(r_{EH} - r_{f,x}) + m_w g r_{EH})\sin\theta_3 \qquad (30)$$

In frontal raise motion, shoulder and elbow joints would generate torques, Fig. 7 demonstrates that spring K_2 connects link 2 and 4 to produce torques to strength the same muscles of free-weight exercise. On the other hand, in shoulder flx-ext exercise with upper limb exoskeleton, a user moves the same as in frontal raise motion. Substituting the same angles, θ_2 and θ_4, of frontal raise motion into the Eqs. (22)-(24), the joint torques of shoulder with exoskeleton are obtained

$$M_{2,fr} = K_1 l_{CP} l_{PB_1} + m_u g r_{u,z} + m_f g r_{f,z} + m_2 g r_{2,z} + m_3 g r_{3,z} + m_4 g r_{4,z} \tag{31}$$

$$\begin{aligned} M_{3,fr} = {} & [m_u g(r_{SE} - r_{u,x}) + m_f g(r_{SE} + r_{EH} - r_{f,x}) - m_3 g(r_{3,x} - r_{SE}) \\ & - m_4 g(r_{4,x} - r_{EH} - r_{SE}) + K_2 l_{SA_2}(r_{SE} + l_{EB_2}) + K_3 l_{SA_3}(l_{EB_3} - r_{SE})]\sin\theta_3 \end{aligned} \tag{32}$$

$$M_{4,fr} = [m_f g(r_{EH} - r_{f,x}) - m_4 g(r_{4,x} - r_{EH}) + K_2 l_{EB_2} l_{SA_2} + K_3 l_{EB_3} l_{SA_2}]\sin\theta_3 \tag{33}$$

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 *sin* θ_3 in Eq. (29) must be equal to Eq. (32) and Eq. (30) equals Eq. (33). The design conditions of spring K_2 and K_3 are obtained as

$$l_{EB_3} = 0 \tag{34}$$

$$l_{EB_2} = r_{EH} \tag{35}$$

$$l_{SA_3} = \frac{-m_3 g r_{EH}(r_{3,x} - r_{SE}) + m_4 g r_{SE} r_{4,x}}{K_3 r_{SE} r_{EH}} \tag{36}$$

$$l_{SA_2} = m_w\left(\frac{g r_{EH}}{K_2 r_{EH}}\right) + \frac{m_4 g(r_{4,x} - r_{EH})}{K_2 r_{EH}} \tag{37}$$

In shoulder flx-ext exercise with the design, the installation of spring K_1 can be set on any position; it can't affect the result of muscle strengthening. The momentum about the axis $z_{1'}$ due to weights of upper limb and exoskeleton's links is same as the momentum in shoulder abd-add; therefore; the design spring condition of K_1 is same as Eq. (28). Eq.(37) also represents a linear proportion relationship between the weight of external load m_w and the length of connected points of spring K_2 with the only adjustment of l_{SA_2} to increase the resistance for training intensity.

3.2.3 Biceps and triceps training from elbow flexion/extension

For elbow flx-ext exercise, dumbbell curl motion principal is a biceps strengthening in free-weight exercise. 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 Eqs. (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

$$\tau_{3,dc} = \tau_{4,dc} = (m_f g(r_{EH} - r_{f,x}) + m_w g r_{EH}) \sin\theta_4 \tag{38}$$

In dumbbell curl motion, joint torques generate on the joints of axes z_3 and z_4, the installation of spring K_3 connects link 2 and link 4 to produce the same joint torques as free-weight exercise (Fig. 7). In training with upper limb exoskeleton for elbow flx-ext exercise, substituting the angles, θ_2 and θ_3, on dumbbell curl motion into the Eqs. (22)-(24), the joint torques with upper limb exoskeleton are obtained. The joint torque of θ_2 same as shoulder flx-ext exercise is expressed as Eq. (31), while the joint torques of θ_3 and θ_4 are shown as

$$M_{3,dc} = [m_f g(r_{EH} - r_{f,x}) - m_4 g(r_{4,x} - r_{EH}) + K_2 l_{EB_2} l_{SA_2} + K_3 l_{EB_3} l_{SA_3}] \sin\theta_4 \tag{39}$$

$$\begin{aligned} M_{4,dc} = {} & [m_f g(r_{EH} - r_{f,x}) - m_4 g(r_{4,x} - r_{EH}) + K_2 l_{EB_2} l_{SA_2} \\ & + K_3 l_{EB_3} l_{SA_3} - K_2 l_{EA_2} r_{SE} + K_3 l_{EB_3} r_{SE}] \sin\theta_4 \end{aligned} \tag{40}$$

The joint torques of θ_3 and θ_4 with upper limb exoskeleton have to be equal to dumbbell curl motion, and the design conditions of spring K_2 and K_3 are obtained as

$$l_{EB_2} = \frac{K_3 l_{EB_3}}{K_2} \tag{41}$$

$$l_{SA_2} = 0 \tag{42}$$

$$l_{SA_3} = m_w\left(\frac{g r_{EH}}{K_3 l_{EB_3}}\right) + \frac{m_4 g(r_{4,x} - r_{EH})}{K_3 l_{EB_3}} \tag{43}$$

On dumbbell curl motion, the increase of resistance is through increasing the weight of external load, m_w; however, due to the linear proportion relationship between m_w and K_3 , the adjustment of spring K_3, i.e., l_{SA_3} , can be used to increase resistant force from Eq. (43) in training with the exoskeleton. The spring design condition of spring K_1 is same as lateral raise motion and shown as Eq. (28).

For strengthening triceps, there is overhead triceps extension in free-weight exercise. In exercising with upper limb exoskeleton, the motion can be performed by elbow flx-ext exercise as well. 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 Eqs. (11)-(13) and (22)-(24) can obtain the joint torques (see Appendix A1), the momentums of free-weight exercise have to be same as the upper limb exoskeleton. Therefore, the design conditions of spring K_2 and K_3, same as the elbow flx-ext exercise for training biceps, are shown as Eqs. (41)-(43). In elbow flx-ext 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.

CHAPTER 4

Preliminary evaluation of the conceptual design

4.1 Joint torques measurement of free-weight exercise

4.1.1 Experimental set-up

The objective joint torques of shoulder and elbow joints are derived from free-weight exercise model; hence, the real values of torques were collected by a series of experiments about shoulder abd-add, flx-ext, and elbow flx-ext exercise. The experiments were conducted to measure the joint torques in three free-weight exercises (lateral raise motion, frontal raise motion, and dumbbell curl motion), and carried out by two healthy subjects (male and female), with the total body weight (TBW) of the male and female subjects being 82 kg and 59 kg, respectively. The length of upper arm and forearm of the male are 280mm and 352mm, and the female 263mm and 309mm. The anthropometric parameters are listed in Table 2.

Table 2 Anthropometric parameters of experimental subjects

Subjects	TBW	Upper arm	Forearm
Male	82kg	280mm	352mm
Female	59kg	263mm	309mm

The resistant force has two levels which are 1kg and 2kg weight respectively for the free-weight exercise. For shoulder abd-add exercise, the movement of the upper limb is driven by shoulder joint about z_1-axis; for shoulder flx-ext exercise, it is driven by shoulder joint about z_2-axis; in elbow flx-ext exercise, the movement of the forearm is driven by the elbow joint about z_3-axis. The measurements of joint torques were achieved by Biodex III isokinetic dynamometer (Biodex III) (Fig. 8) [27, 28], which is an isokinetic dynamometer with an electrically controlled servomechanism commonly used in clinical and research settings.

Fig. 8 The Biodex III isokinetic dynamometer [27]

During the experimental process, care must be taken in order to obtain accurate data for some random errors may cause the deviation of data acquisition. The accuracy of the experiment depends on the alignment between Biodex dynamometer and human joint. However, the shoulder joint is not a fixed point due to shoulder girdle’s motion. It’s also difficult for human subjects to keep the free-weight exercise described earlier on the same plane during the exercise, and the physical state of subjects would be different every day. All these variables would be controlled as good as possible by setting the protocol, monitoring the displayed graph and manipulating of Biodex III while conducting the experiments. In addition to the above-mentioned considerable attentions were given to the conformity and well planning of the experiments.

4.1.2 Measurement procedures

Joint torques of shoulder and elbow exerted by the right upper limb were measured in 3 different types of free-weight exercise. In shoulder abd-add exercise (Fig. 9), the motion angle ranges from 90 degree to 180 degree and then reverses. In shoulder flx-ext exercise (Fig. 10), the joint angle ranges from 0 degree to 90 degree and then back to the beginning position of the motion. In elbow flx-ext exercise (Fig. 11), there is a joint angle limit ranging from 90 degree to 180 degree in Biodex III to carry out the standard procedure, so the joint angle in θ_4 is chosen in ranges from 100 degree to 150 degree and then back to 100 degree.

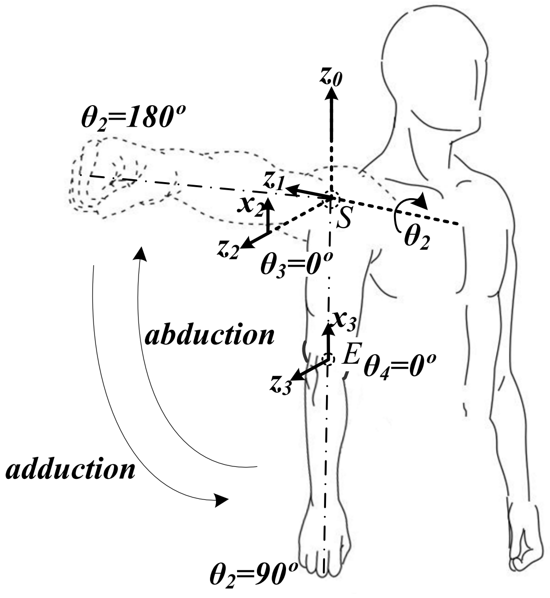


Fig. 9 A diagram of shoulder abd-add exercise in experiment

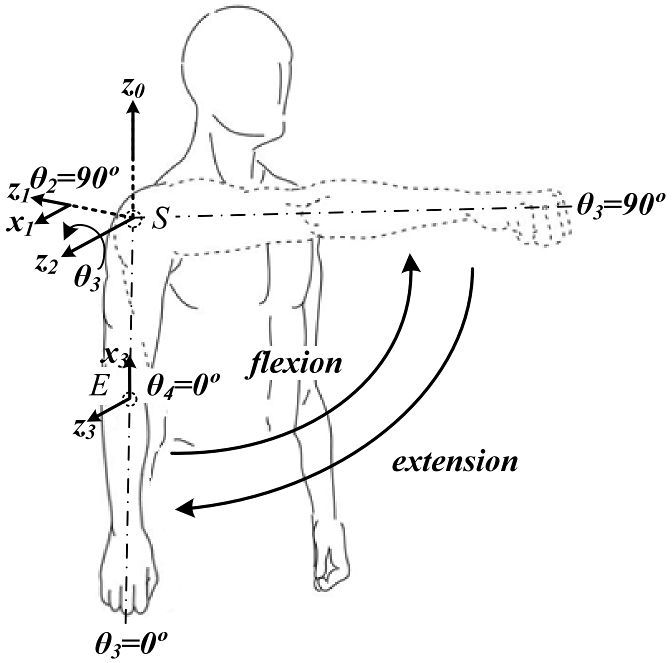


Fig. 10 A diagram of shoulder flx-ext exercise in experiment

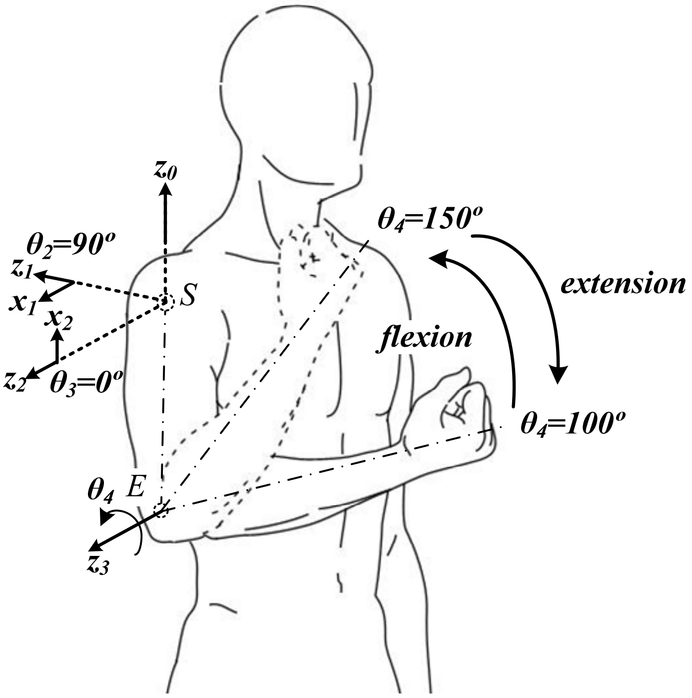


Fig. 11 A diagram of elbow flx-ext exercise in experiment

The joint torques of three exercises were measured by isokinetic mode of Biodex III. First, the joint torques of three exercises without free-weights were measured. Then, the same exercise with free-weights was repeated to collect the data of joint torques. The gravitational torques contributed from free-weights of each exercise were then obtained simply by subtracting the first data from the second data. Since the gravitational torques from upper limb were deducted while computing the gravitational torques from free-weights, the torques from upper limb of the θ_i angles can be computed by multiplying the maximum torques which were measured from Biodex III with cos θ_i. By adding it together with the gravitational torques contributed from free-weights, the objective joint torques of free-weight exercise of three exercises from both free-weights and upper limb were then obtained.

4.2 Simulation of the conceptual exoskeleton design

The upper limb exoskeleton for muscular exercise is designed by four links and three zero-free-length springs in which the springs provide not only resistant force for training but balance of the weight of links. The preliminary conceptual design was carried out by 3D CAD design software, and the materials of the links are made of aluminum in this study. The material characteristics of links were set in the CAD software to learn the inertia parameters of the upper limb exoskeleton. The masses and corresponding coordinates of the mass centers of each link are listed in Table 3.

Table 3 Inertia parameters of the upper limb exoskeleton

links	mass(kg)	r_x (mm)	r_y (mm)	r_z (mm)
1	0.502	-45	82	25
2	1.233	-13	29	-18
3	0.202	143	0	-75.4
4	0.418	94	0	-50.6

The resistance of the design is generated by adjusting the locations of springs rather than change the stiffness of springs. This design is expected to provide light resistance for muscle strength recovery of patients and heavy enough for muscle strengthening of health people. In this study, the maximum resistant force is designed on 68.6 N (7 kg weight dumbbell), it is important to choose suitable stiffness of springs.

In preliminary conceptual design of the upper limb exoskeleton, interference among different links during exercise needs to be considered. For example, the attached point B_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_{EB_3} is designed as 150mm which is shorter than the length of upper arm. The spring adjustable points are limited in the range of 40mm to 120mm which it doesn't become a fine-tuning situation and it's not too long to adjust. The adjustable lengths l_{A_1C}, l_{SA_2} and l_{SA_3} of springs K_1, K_2 and K_3 are designed on link 2 which is a reasonable locations in the exoskeleton. On the other hand, the length, l_{PB_1}, of attached point of spring K_1 together with link 1 is designed as 100mm which shorter than the adjustable length. Consider above-mentioned the limitations and the mass properties of linkages along with anthropometric parameters of humans to Eq. (27), the range of spring stiffness of K_1 can be obtained as

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

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

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

$$1.323\ \text{N/mm} \le K_2 \le 2.901\ \text{N/mm} \tag{46}$$

The K_1, K_2 and K_3 springs available within its stiffness ranges can be selected in this design. In practical implementation of this design, we chose chose the following constant stiffness springs from the catalog [36] of standard springs: K_1 (4.704N/mm (0.480 kgw/mm)), K_2 (1.107N/mm(0.103 kgw/mm)) and K_3 (1.392N/mm(0.142 kgw/mm)).

Design parameters of the upper limb exoskeleton depend on the anthropometric parameters associated with the user's upper limb. The segmental weights of upper arm and forearm are based on Clauser et al. [26] who had proposed the following regression model for the estimation of these parameters:

$$m_u = 0.0274 \times (\text{TBW}) - 0.01 \tag{47}$$

$$m_f = 0.0233 \times (\text{TBW}) - 0.01 \tag{48}$$

where TBW is the total body weight.

According to the anthropometric parameters of male and female subjects in experiment, the exact values of l_{A_1C}, l_{SA_2}, and l_{SA_3} for 1kg and 2kg weight resistances for the upper limb exoskeleton are listed in Table 4. 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.

Table 4 The adjustable length of springs for 1 and 2kg weight resistance

Muscle strengthening exercise	Adjustments of springs (mm) (Resistance:1kg/2kg)	
	Male	female
Shoulder abd/add exercise, l_{LB}	6/16	5/14
Shoulder flx/ext exercise, l_{SF}	6/15	6/15
Elbow flx/ext exercise, l_{SC}	11/28	10/25
All exercise, $l_{BS'}$	11	

4.3 Comparison between theoretical analysis and simulation

The preliminary exoskeleton design in ADAMS was based on the spring design conditions which were derived from the objective joint torques of free-weight exercise. The objective joint toques of free-weight exercise in chapter 2.2, and Eqs. (25), (29) and (38) are the joint torques for shoulder abd-add, flx-ext, and elbow flx-ext exercise, respectively. The theoretical values were learned by substituting the anthropometric parameters of experimental subjects into the equations of objective joint torques and listed in Tables 5, 6, and 7 for shoulder abd-add, flx-ext, and elbow flx-ext exercise, respectively. The mass centers of upper arm and forearm were calculated according to Clauser et al. [26] who had proposed formulas for the estimation (see Appendix A2).

From Tables 5, 6, and 7, the theoretical values of joint torques appeared to be generally compatible with the data obtained from simulation of conceptual exoskeleton design; the results lend support to the conceptual design in ADAMS. And the difference between theoretical and simulated joint torques are near to zero, elbow flx-ext exercise especially.

Table 5 The comparison and difference between theoretical and simulated data for shoulder abd-add exercise with 1kgw resistance

Degrees	Male			Female		
	$\bar{\tau}$	$\bar{\mathrm{M}}$	D	$\bar{\tau}$	$\bar{\mathrm{M}}$	D
90	0	0	0	0	0	0
108	5916	6069	2.59	4229	4342	2.67
126	11253	11544	2.59	8044	8266	2.76
144	15489	15889	2.58	11071	11380	2.79
162	18028	18678	3.61	13015	13381	2.81
180	19145	19639	2.58	13684	14072	2.84

* $\bar{\tau}$: theoretical joint torques; $\bar{\mathrm{M}}$: simulated joint torques; D: $\frac{\left|\bar{\tau}-\bar{\mathrm{M}}\right|}{\bar{\tau}}\times 100\%$

Table 6 The comparison and difference between theoretical and simulated data for shoulder flx-ext exercise with 1kgw resistance

Degrees	Male			Female		
	$\bar{\tau}$	$\bar{\mathrm{M}}$	D	$\bar{\tau}$	$\bar{\mathrm{M}}$	D
0	0	0	0	0	0	0
18	5916	6010	1.59	4229	4290	1.44
36	11253	11433	1.6	8044	8161	1.45
54	15489	15770	1.81	11071	11232	1.45
72	18028	18332	1.69	13015	13204	1.45
90	19145	19445	1.57	13684	13884	1.46

* $\bar{\tau}$: theoretical joint torques; $\bar{\mathrm{M}}$: simulated joint torques; D: $\frac{\left|\bar{\tau}-\bar{\mathrm{M}}\right|}{\bar{\tau}}\times 100\%$

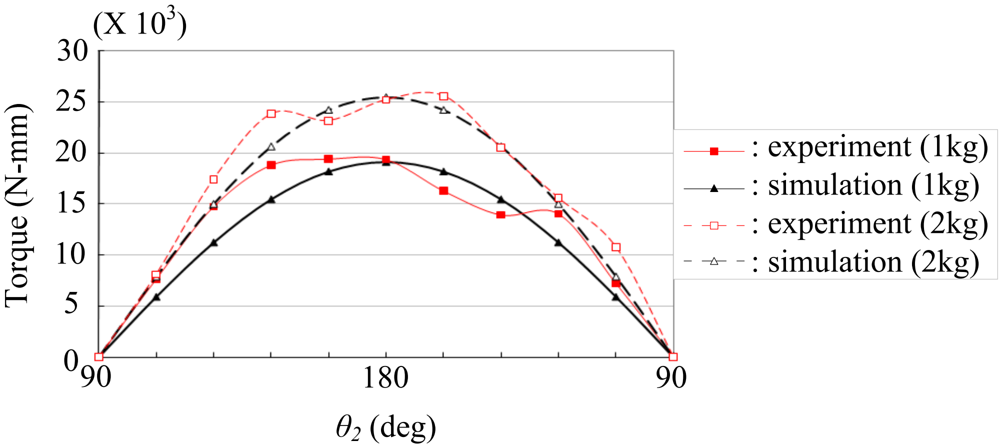
Table 7 The comparison and difference between theoretical and simulated data for elbow flx-ext exercise with 1kgw resistance

Degrees	Male			Female		
	$\bar{\tau}$	$\overline{\mathrm{M}}$	D	$\bar{\tau}$	$\overline{\mathrm{M}}$	D
100	6551	6548	0	5007	5006	0
110	6251	6251	0	4777	4777	0
120	5761	5761	0	4403	4403	0
130	5096	5096	0	3894	3894	0
140	4276	4276	0	3268	3268	0
150	3326	3326	0	2542	2542	0

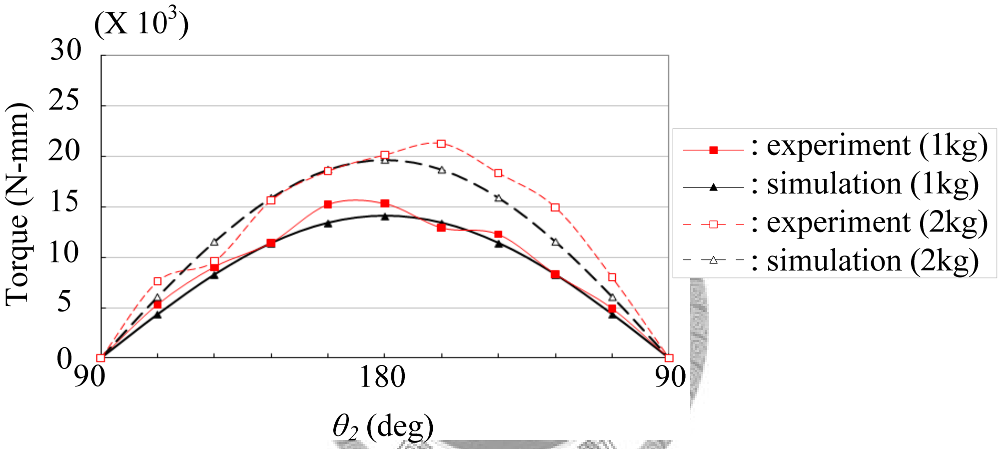
* $\bar{\tau}$: theoretical joint torques; $\overline{\mathrm{M}}$: simulated joint torques; D: $\frac{\left|\bar{\tau}-\overline{\mathrm{M}}\right|}{\bar{\tau}} \times 100\%$

4.4 Results of experimental and simulated data

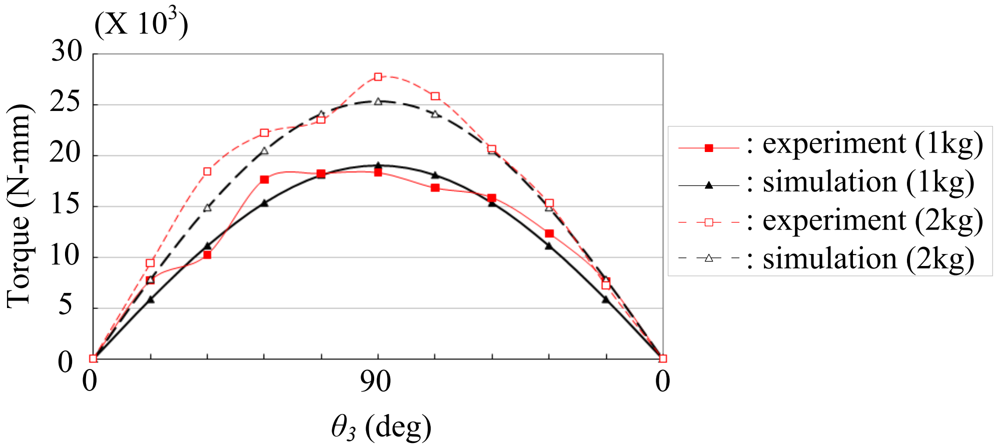
Fig. 12 shows the comparisons between the joint torques of objective free-weight exercise for the experiments and the upper limb exoskeleton from ADAMS model. In Fig. 12(a)-(d), the peak joint torques are happened on 180 degree for the shoulder abd-add exercise and 90 degree for flx-ext exercise. The joints would generate higher torques when the upper limb straighten at the horizontal position which the moment arm has the longest distance which is perpendicular to the resistant force about the joint. Such an explanation can be applied to elbow flx-ext exercise, the forearm flexed from nearly horizontal positions toward human shoulder then reversed. As shown in Fig. 12(e)-(f), the joint torques at points of beginning and ending are the highest, and the lowest joint torque happen on the middle point of a exercise period.



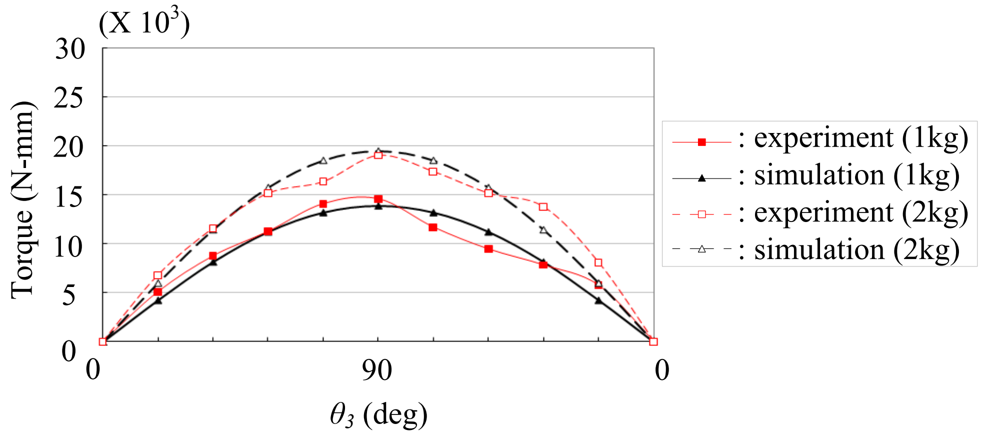
(a) Shoulder abd-add exercise (male)



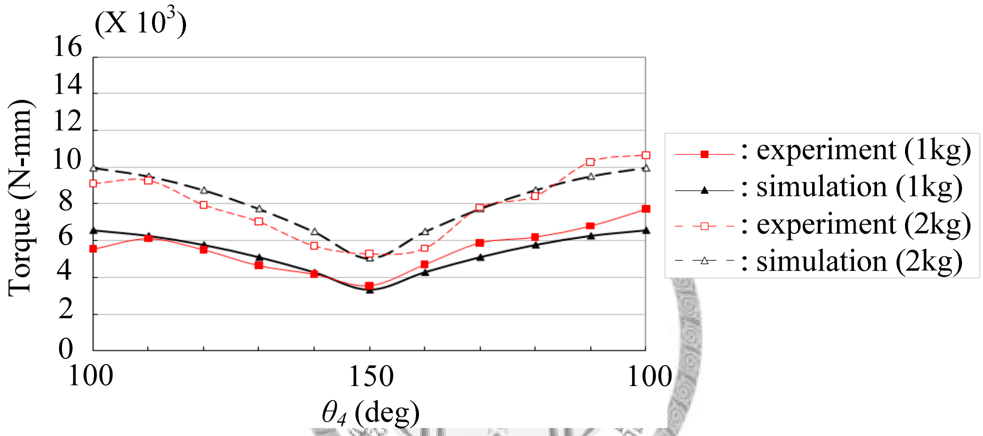
(b) Shoulder abd-add exercise (female)



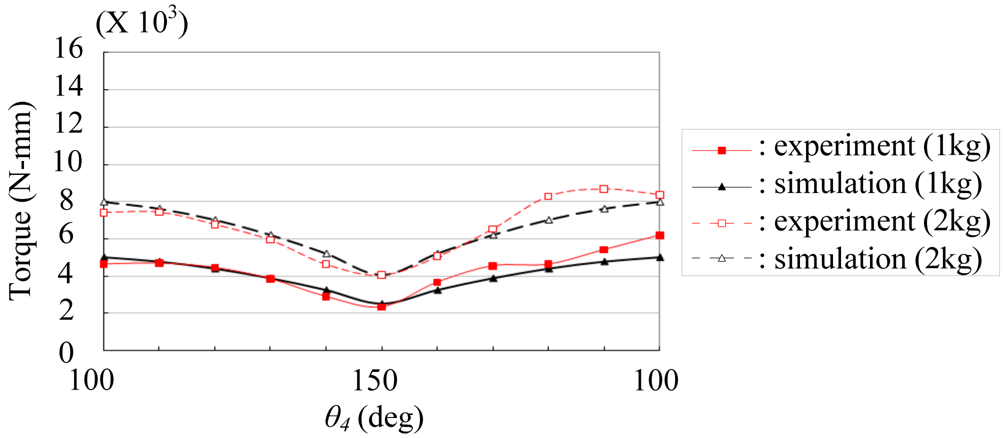
(c) Shoulder flx-ext exercise (male)



(d) Shoulder flx-ext exercise (female)



(e) Elbow flx-ext exercise (male)



(f) Elbow flx-ext exercise (female)

Fig. 12 The experimental and simulated data of joint torques with 1kg and 2kg resistance

The simulation results from ADAMS are simulated torques from the resistance and the weight of upper limb; it means the minimum of torques to resist and move for human subjects. In practical, human subjects tend to exert more force to exercise; that is, the data acquired from the experiments would be slightly higher than ADAMS. In elbow flexion motion, both two subjects seemingly did not exert enough force to withstand the resistance at experiments, so the data obtained are slightly lower than the ADAMS model. The peak torques with the upper limb exoskeleton are nearly equivalent to those of the experimental data for all exercises (Fig. 12). Except for shoulder flx-ext exercise of male at 2kg resistance, the peak torques (25339N-mm) were slightly lower than the experimental data (27742N-mm) and the difference was 8.66%.

Tables 8, 9 and 10 provide the relative errors of joint torques in shoulder abd-add, flx-ext and elbow flx-ext exercise, respectively. The relative errors are the ratio of the difference between simulated data and experimental data to the experimental data. The values of simulated and experimental joint torques are listed in appendix (See Appendix A3). The results reflected in Tables 8 and 9, indicate that the experimental data at the initial and final states are slightly higher than simulated data. As a whole, the relative errors didn’t exceed 25% for angles measured and the results suggest that there are acceptable tolerances between the tendency of experimental and simulated joint torque curves.

Table 8 The relative errors of joint torques in shoulder abd-add exercise

Angle (deg)	Relative errors (%)			
	Male		Female	
	1kg	2kg	1kg	2kg
90	0	0	0	0
108	22.49	2.59	18.46	19.93
126	23.65	13.94	8.58	20.59
144	17.64	13.34	0.56	1.80
162	6.09	4.53	12.16	1.07
180	1.07	1.00	8.12	2.22
162	11.84	5.31	3.68	12.00
144	11.18	0.65	7.15	13.09
126	19.76	3.63	0.54	22.60
108	17.94	19.64	11.48	24.34
90	0	0	0	0

Table 9 The relative errors of joint torques in shoulder flx-ext exercise

Angle (deg)	Relative errors (%)			
	Male		Female	
	1kg	2kg	1kg	2kg
0	0	0	0	0
18	23.82	16.81	16.09	11.32
36	8.66	19.11	6.67	1.16
54	12.99	7.78	0.17	4.04
72	0.71	2.47	6.24	13.45
90	4.00	8.66	4.80	2.47
72	7.61	6.87	13.02	6.69
54	3.23	1.01	18.84	4.09
36	9.88	2.74	4.37	16.76
18	23.42	8.27	25.81	24.12
0	0	0	0	0

Table 10 The relative errors of joint torques in elbow flx-ext exercise

Angle (deg)	Relative errors (%)			
	Male		Female	
	1kg	2kg	1kg	2kg
100	18.10	9.21	7.84	7.68
110	2.11	2.31	1.90	2.57
120	4.54	10.12	1.23	3.61
130	9.59	10.02	1.22	4.52
140	2.25	13.63	12.73	12.10
150	6.42	4.45	8.54	0.42
140	9.06	16.28	10.91	3.13
130	13.52	0.83	14.38	4.94
120	7.17	3.91	4.96	15.11
110	8.24	7.74	11.75	12.05
100	15.22	6.71	19.15	4.54

CHAPTER 5

Embodiment design of the upper limb exoskeleton

The link length r_{SE} and r_{EH} of upper arm and forearm can be measured via access to many database of anthropometry. According to the anthropometry resource from Naval biodynamics lab. [23], Clauser et al. [24] and the institute of occupational safety & health in Taiwan [25], the link lengths of upper arm and forearm together with the total body weight for the small, mid, and large sized human beings are listed in Table 11.

Table 11 Anthropometric parameters of upper limb

Dimension descriptions	Small	Mid	Large
Upper arm (r_{SE}, mm)	224	255	286
Forearm (r_{EH}, mm)	267	317	368
Total body weight (TBW, kg)	44.3	62.1	79.9

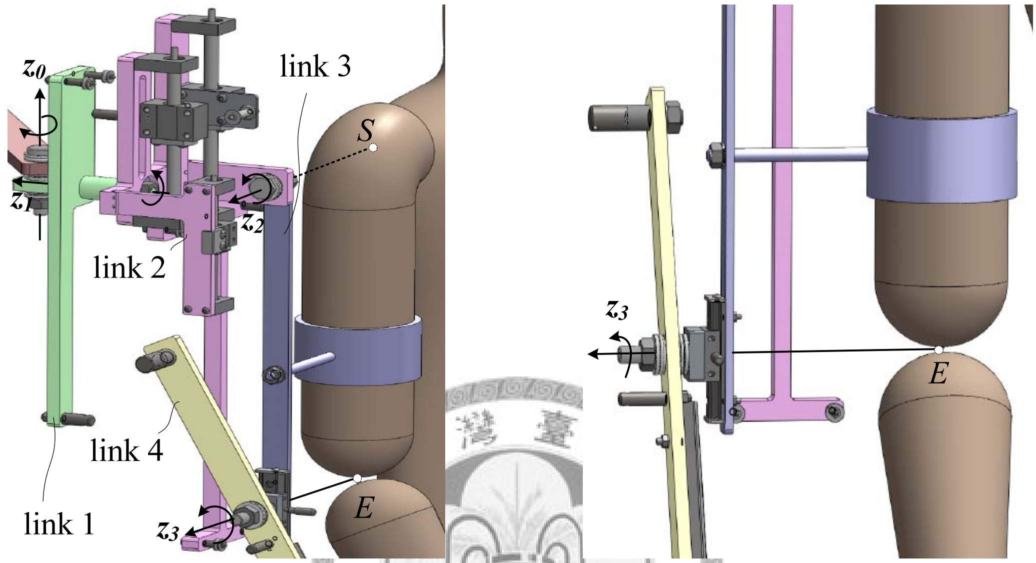
The spring design parameters of the exoskeleton are functions of the lengths of upper arm and forearm and mass properties of links. Utilizing the values of m_u, m_f, r_{SE}, r_{EH}, K_1, K_2, and K_3 along with the parameters of links, the range of spring adjustable points are listed in Table 12. Meanwhile, 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_{SA_3} can be regarded as zero in this exercise.

Table 12 Detailed spring design parameters of the exoskeleton

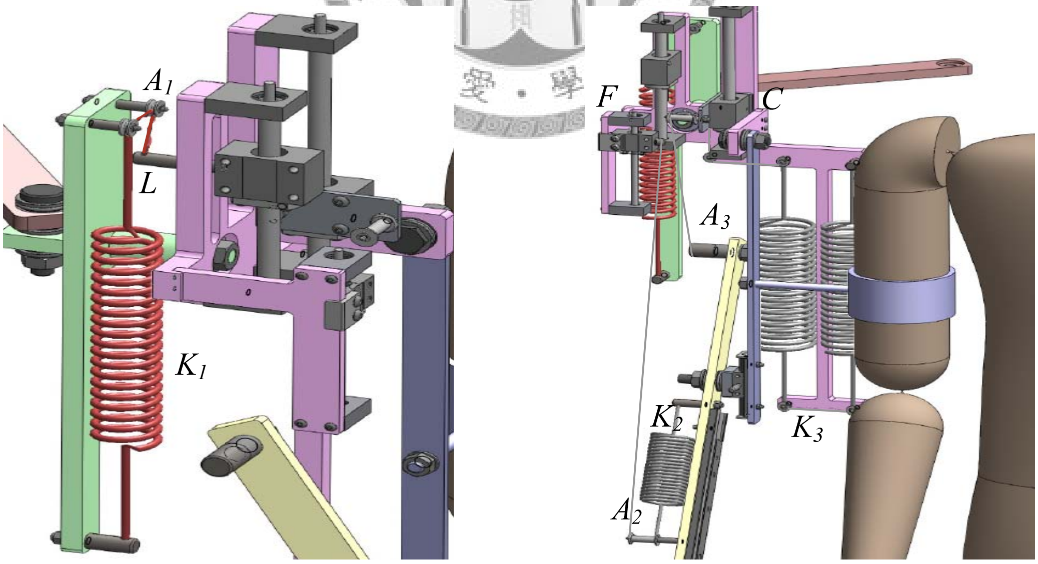
	Spring design parameters (mm) (Resistance:1kg~7kg)			
	Adjustments of springs	Small	Mid	Large
Shoulder abd/add exercise	l_{A1P}	5~80		
	l_{PB1}	100		
Shoulder flx/ext exercise	l_{SA2}	6~60		
	l_{EB2}	267	317	368
	l_{SA3}	0		
	l_{EB3}	0		
Elbow flx/ext exercise	l_{SA2}	0		
	l_{EB2}	188		
	l_{SA3}	9~120		
	l_{EB3}	150		
All exercise	l_{CP}	11		

In embodiment design of the device, the arrangement of three revolute joints for 3-DOF shoulder joint is illustrated in Fig. 13(*a*). The revolute joints of axes z_0, z_1, and z_2 are achieved by thrust bearings for decreasing the defects of clearance. The elbow joint is performed 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 length of forearm link is also adjusted by a linear slide for suiting different individuals. The CAD drawing is shown in Fig. 13(*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 link 1 and point L on link 2. An embodiment design of spring K_1 is illustrated in Fig. 13(*c*), and 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. 13(*d*). For increasing the intensity of exercise, the installation in link 2 is adjusted by three lead screws. Possibility of the interference between links and springs during exercise is considered and eliminated.



(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

Fig. 13 Embodiment design of the upper limb exoskeleton

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

CHAPTER 6

Conclusion

In this study an upper limb exoskeleton design for free-weight exercise to strengthen the principal muscles with overextension injury prevention is presented. Linear relationship between the weight of external load and the attached spring is obtained. In stead of changing the weight of dumbbell, 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 joints with the exoskeleton are expected to be equal to the objective joint torques obtained from a model of free-weight exercise. By a series of experimental measurement about joint torques of shoulder abduction-adduction, flexion-extension and elbow flexion-extension free-weight exercise, it proves that there are acceptable tolerances between the tendency of experimental and simulated joint torque curves. According to the results of evaluation, this study provides the embodiment design of the upper limb exoskeleton with adjustable upper arm and forearm length suitable for the normal sized human beings, and by the arrangement of small-inertia springs, it is capable of preventing the muscle injuries caused from the huge inertia.

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Appendix

A1. Joint torques of elbow flx-ext exercise for training triceps

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. Angles of θ_2 and θ_3 are substituting into the Eqs. (11)-(13) which obtain the joint torque of θ_2 is zero, and the joint torques of θ_3 and θ_4 are equalized as follows

$$\tau_{3,tri} = \tau_{4,tri} = -(m_f g(r_{EH} - r_{f,x}) + m_w g r_{EH}) \sin\theta_4 \tag{A1.1}$$

The same angles of θ_2 and θ_3 are substituted into the Eqs. (22)-(24), and the joint torques of elbow joint with upper limb exoskeleton are

$$\begin{aligned} M_{3,tri} = -[&m_f g(r_{EH} - r_{f,x}) - m_4 g(r_{4,x} - r_{EH}) + K_2 l_{EA_2} l_{SF} \\ &+ K_3 l_{EA_3} l_{SC}] \sin\theta_4 \end{aligned} \tag{A1.2}$$

$$\begin{aligned} M_{4,tri} = -[&m_f g(r_{EH} - r_{f,x}) - m_4 g(r_{4,x} - r_{EH}) + K_2 l_{EA_2} l_{SF} \\ &+ K_3 l_{EA_3} l_{SC} + K_2 l_{EA_2} r_{SE} - K_3 l_{EA_3} r_{SE}] \sin\theta_4 \end{aligned} \tag{A1.3}$$

A2. The mass centers of upper arm and forearm for experimental subjects

The mass centers of upper arm and forearm are according to Clauser et al. [26] who had proposed following equations for the estimation

$$\begin{aligned} r_{SE} - r_{u,x} = r_{SM_u} + \Delta_S^* &= .329 \times (\text{humerus rad. length}) - .25 \times (\text{upper arm cir.}) \\ &+ 2.827 \times (\text{elbow breadth}) - 6.168, \quad \varepsilon_{SMu} = .72 + \varepsilon_{\Delta S} \end{aligned} \tag{A2.1}$$

$$\begin{aligned} r_{EH} - r_{f,x} = r_{EM_f} &= 1.617 \times (\text{wrist breadth}) - .585 \times (\text{radiale - stylion length}) \\ &- .331 \times (\text{forearm cir.}) + .510, \quad \varepsilon_{EMf} = .46 \end{aligned} \tag{A2.2}$$

where r_{SM_u} is the distance from shoulder joint to mass center of upper arm; r_{EM_f} is the distance from elbow joint to mass center of forearm; ε_{SM_u} and ε_{EM_f} represent the standard error of the estimates for r_{SM_u} and r_{EM_f}, respectively. Note that Δ^*_S in Eq. (A2.1) is the distance from the acromion to the shoulder pivot. The value and estimated error, Δ^*_S and $\varepsilon_{\Delta S}$, are 3.8 cm and 0.2 cm, respectively [23].

The related anthropometric parameters of experimental subjects for deriving the mass centers of upper limb are listed in Table A2.1.

Table A2.1 The measured dimensions of upper limb for subjects

	Male	Female
Humerus rad. length	330 mm	303 mm
Upper arm cir.	270 mm	239 mm
Elbow breadth	340 mm	287 mm
Wrist breadth	280 mm	234 mm
Radiale-stylion length	100 mm	80 mm
Forearm cir.	60 mm	52 mm

The mass center of upper arm and forearm, r_{SM_u} and r_{EM_f}, for male subject are 206.6 mm and 172mm, respectively. For female subject, r_{SM_u} and r_{EM_f} are 154mm and 152mm.

A3. The values of simulated and experimental joint torques

The joint torques of simulated data ($\overline{\mathrm{M}}$) and experimental data (E) for male and female subjects in shoulder abd-add, flx-ext and elbow flx-ext exercise with 1kgw and 2kgw resistant force are listed in Tables A3.1, A3.2 and A3.3, respectively.

Table A3.1 The values of simulated and experimental joint torques in shoulder abd-add exercise

Angle (deg)	Joint torques (N-mm)							
	Male				Female			
	1kg		2kg		1kg		2kg	
	$\overline{M}$	E	$\overline{M}$	E	$\overline{M}$	E	$\overline{M}$	E
90	0	0	0	0	0	0	0	0
108	5916	7633	7906	8116	4342	5325	6075	7587
126	11253	14739	15006	17436	8266	9042	11561	9587
144	15489	18807	20632	23807	11380	11444	15915	15634
162	18208	19389	24209	23159	13381	15233	18712	18513
180	19145	19352	25447	25196	14072	15316	19677	20123
162	18208	16280	24209	25567	13381	12906	18712	21264
144	15489	13932	20632	20499	11380	12256	15915	18312
126	11253	14025	15006	15572	8266	8311	11561	14937
108	5916	7209	7906	10758	4342	4905	6075	7999
90	0	0	0	0	0	0	0	0

Table A3.2 The values of simulated and experimental joint torques in shoulder flx-ext exercise

Angle (deg)	Joint torques (N-mm)							
	Male				Female			
	1kg		2kg		1kg		2kg	
	$\overline{M}$	E	$\overline{M}$	E	$\overline{M}$	E	$\overline{M}$	E
0	0	0	0	0	0	0	0	0
18	5875	7712	7830	9412	4260	5077	6023	6792
36	11141	10253	14894	18413	8161	8744	11456	11591
54	15356	17648	20499	22228	11232	11251	15767	15155
72	18098	18228	24099	23518	13204	14083	18535	16338
90	19045	18312	25339	27742	13884	14584	19489	19020
72	18098	16818	24099	25878	13204	11683	18535	17372
54	15356	15868	20499	20708	11232	9451	15767	15148
36	11141	12363	14894	15313	8161	7819	11456	13762
18	5875	7672	7830	7232	4260	5614	6023	8055
0	0	0	0	0	0	0	0	0

Table A3.3 The values of simulated and experimental joint torques in elbow flx-ext exercise

Angle (deg)	Joint torques (N-mm)							
	Male				Female			
	1kg		2kg		1kg		2kg	
	$\overline{M}$	E	$\overline{M}$	E	$\overline{M}$	E	$\overline{M}$	E
100	6551	5547	9948	9109	5007	4643	7989	7419
110	6251	6122	9493	9279	4777	4688	7623	7432
120	5761	5511	8748	7944	4403	4458	7025	6780
130	5096	4650	7738	7033	3894	3847	6214	5945
140	4276	4182	6493	5714	3268	2899	5214	4651
150	3326	3554	5051	5286	2542	2342	4056	4073
140	4276	4702	6493	5584	3268	3668	5214	5056
130	5096	5893	7738	7803	3894	4548	6214	6537
120	5761	6206	8748	8419	4403	4633	7025	8275
110	6251	6812	9493	10289	4777	5413	7623	8667
100	6551	7727	9948	10664	5007	6193	7989	8369