ENERGY ANALYSIS OF DIFFERENT TRUNK TILTING ANGLES ON JOINT LOADING DURING FALL ON AN OUTSTRETCHED HAND

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ABSTRACT

From previous researches, studies on the forward fall had focused on the relationship between the joint loading and position of the forearm and elbow. Previous studies also stressed the importance of energy absorption by the shoulder and elbow during the forward fall. However, the effects of different tilting angles on joint loading of the upper extremity had not been presented. This study investigated the effects of different tilting angles on joint loading of the upper extremity during fall on an outstretched hand. The absorbed energy at Ts, T1, T2 and Te were analyzed. Ten healthy young males were selected in this study. Subjects were adjusted to different trunk tilting angles of 0°, 10°, 20° and 30° with a custom-made suspension system with an outstretched hand of 5 cm height above the ground. The expert vision motion system with 6 CCD cameras and one force plate were used to collect kinetics and kinematics data. The results showed that shoulder would absorb the most impact energy and followed by wrist and elbow. The time period at T2 to Te absorbed more energy in every joint.

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1. INTRODUCTION

When a fall occurred, people often used upper extremities to protect the head and trunk from impact injuries[8,11,16]. Falling onto the outstretched hand was the major cause of upper extremity injury, including approximately 90% of fractures at the distal radius, humeral neck, and supracondyles of the

elbow[9,13]. The fall-related upper extremity fractures have a bimodal age distribution in young males and older females [3,12]. Robinovch and Chiu [1] measured impact forces during forward fall onto the outstretched hand. From the reports, ground reaction forces are governed by an initial high-frequency peak (Fmax1) and followed by a low-frequency oscillation (Fmax2). They consider this behavior could be demonstrated using a two degree of freedom lumped parameter mathematical model to simulate falls on the outstretched hand. Neglecting the elbow motion, this mathematical model predicted that a fall from over 0.6m heights would result in higher risk for wrist fracture.

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Other study revealed that the fall arrest strategy would affect peak hand impact force in a forward fall[4]. As reported by Chou *et al.*[2], elbow flexion, instead of outstretch hand, during a fall would decrease the ground reaction force effectively. They suggested that the motion of elbow flexion afforded the similar function of the combination of damper and spring. However, falling with trunk tilting might be most popular way in daily activities and seldom studies were mentioned about this case. The purpose of this study is to investigate the joint force and moment when trunk was tilting during a fall. Four different trunk tilting angles, including 0° , 10° , 20° and 30° , were applied in this study.

2. METHODS

2.1 Subjects and Experimental Protocol

Ten male subjects were included in this study. The basic data of subjects were ranged from 16 to 20 years (mean 18.0, SD 2.0) of age, 62 to 83 kg (mean 71.1, SD 6.9) of body weight, and 165 to 183 cm (mean 175.4, SD 6.0) of body height. All subjects were right hand dominant without musculoskeletal disorder of the upper extremity.

The Expert Vision motion system (Motion Analysis Corp., Santa Rosa, CA, USA), consist of six cameras (120 Hz) and one force-plate with 1000 Hz sampling rate (Type 9281B, Kistler Instrument Corp., Winterthur, Switzerland), were used to record relative joint positions and ground reaction forces. A set of eleven reflective markers was placed on selected anatomic landmarks on the subject (as shown in Figure 1). These anatomic landmarks were assumed as rigid body and without relative motion between them. These markers included trunk (cervical vertebra 7, thoracic vertebra 4 and acromion), upper arm (acromion process, medial and lateral epicondyles of the elbow), forearm (medial and lateral epicondyles of the elbow, ulnar styloid processes), and hand (radial and ulnar styloid processes, third metacarpal bone). In addition, a triangular frame with three-markers was placed on the upper arm in order to minimize the possible errors due to skin movement of epicondyles during experiments.

In order to find out the upper extremity joints energy absorption with different trunk tilting angles during a fall, all subjects were tested for four different trunk tilting angles (0° , 10° , 20° and 30°). In the beginning, the subject was placed with knees in contact with the ground. Then the subject was suspended with a custom-made suspension system and fell from a height of 5cm (i.e. distance between the outstretched hand and the force plate) with one hand. The angle between the trunk and the upper arm is maintained at

Fig. 1 Custom-made suspension system ('○' show forward markers and '●' show forward markers. T4 : 4th thoracic vertebra. C7 : 7th cervical vertebra. AC : Acromion. EL : lateral epicondyle of the humerus. EM : medial epicondyle of the humerus. WL : styloid process of radius. WM : styloid process of ulna. H3 : 3rd metacarpal bone. U、P、M : marker triad)

60° forward flexion of the shoulder (Figure 2). Finally, the subject was tested with an outstretched hand following the procedures mentioned above. Furthermore, a questionnaire was also designed to record each subject's sensation of pain or discomfort index (ranged from 0 to 10) during the impact. High value of the index represented most painful or discomfort.

2.2 Assumptions

Three assumptions were made in this experiment: (1) each segment of upper extremity was assumed as rigid body with constant density; (2) each joint was assumed to have three rotational degrees of freedom; (3) all frictions, including air and rope/pulley (of the safety restraint system), were neglected.

2.3 Theorem and Govern Equation

Theorem of this study is based on Newton's second law of motion, and the free body diagram of each segment as shown in Figure 3.

$$\text{Joint force : } \vec{F}_r + \vec{F}_s + m\vec{g} = m\vec{a}$$

$$\text{Joint moment : } \vec{M}_r + \vec{M}_s + \vec{r}_r \times \vec{F}_r + \vec{r}_s \times \vec{F}_s + \vec{\omega} \times (I\vec{\omega}) = I\vec{\alpha}$$

$$\text{Joint power : } P(t) = \vec{M}(t) \cdot d\vec{\omega}(t) = \vec{M}(t) \frac{d\vec{\theta}(t)}{dt}$$

$$\text{Joint energy} : \int \bar{M}(t) \cdot \frac{d\bar{\theta}(t)}{dt} dt = \int \bar{M}(t) \cdot d\bar{\theta}(t)$$

The symbols of the equilibrium equations are explained as below:

$\bar{F}_r$: proximal joint force

$\bar{F}_d$: distal joint force.

$m\bar{g}$: gravity force of the local segment.

$m\bar{a}$: effective force.

$\bar{M}_r$: proximal joint moment.

$\bar{M}_d$: distal joint moment.

$\bar{r}_d$: position vector of the distal end moment arm of the segment.

$\bar{r}_r$: position vector of the proximal end moment arm of the segment.

$\bar{\omega}$: angular velocity of the local segment.

$\bar{\alpha}$: angular acceleration of the local segment.

I : mass moment of inertia.

2.4 Data Reduction

Laboratory-developed kinematics and kinetics software were used to calculate the joint angles, resultant forces and moments of the wrist, elbow and shoulder. A three-segment model, i.e. hand, forearm and upperarm, was employed in the analysis. Three joints angles, hinge angle, rotational angle and horizontal deviation were calculated using Euler's method with a y-x-z rotational sequence based on the attached markers. Segment mass and inertia data were estimated by human anthropometry[5]. Angular velocity and acceleration were calculated with Euler's

Fig. 3 The free body diagram of upper extremity.

parametric method [7]. The joint loadings were then obtained using inverse dynamic procedures with the Newton-Euler equations. A generalized cross-validation spline smoothing (GCVSPL) routine with a cutoff frequency of 6 Hz was used for data smoothing [15]. Joint angles and joint forces of the wrist, elbow and shoulder as functions of time during the impact period were calculated and then used for analysis.

2.5 Data Analysis

Statistical analyses (ANOVA), with statistical significance set at the 5% level, were used to calculate for the ground reaction force, joint angle and joints force. In order to evaluate the vertical force data of the ground reaction force (GRF), the entire time period of each single test was divided into three time phases: (1) the Pre-Impact phase, lasting from T_0 to T_s ; (2) the Impact phase, lasting from T_s to T_e ; (3) the Post-Impact phase, lasting from T_e to the end of the experiment. T_0 was the instant when the fall began. T_s was the instant when the ground reaction force (GRF) rose above baseline noise level. T_e was defined as the end of the final rapid decrease in GRF prior to the steady state response (Figure 4).

3. RESULT

3.1 Energy Absorption and Joint Energy

Energy absorption was defined as elbow joint energy divided by shoulder joint energy (Elbow/Shoulder) and wrist joint energy divide by shoulder joint energy (Shoulder/Wrist). The energy

Fig. 2 The experimental arrangement.

Fig. 4 Typical GRF data of neutral posture.

absorption from Ts to Te period among four groups were not significantly different ($P < 0.05$) (Table 1). During Ts to T1 period, the impact energy among wrist, elbow and shoulder joint were smaller than other period, and there were not significantly different among four groups. During Ts to T2 period, the value was also not significantly different among four groups.

During Ts to Te period, the value was increased obviously, but there was no significant difference among four groups. The period from T2 to Te is the mean period for joint to absorb impact energy during falls. Even wrist, elbow or shoulder joint energies were increased obviously in this period, there was no significant difference among four groups in every time period (Table 3). The results of questionnaire showed that 0° group has the lower uncomfortable index (Table 4).

4. DISCUSSION

During falls, the impact energy would be absorbed by upper extremity joints' motion as the effect of damper. In this study the subjects were requested to be completely outstretched their elbow in order to protect the direct impact to body and head. However, stronger impact force resulted in fewer elbow angle motion that may be affected the energy absorption in elbow joint. Wrist joint had absorbed energy by forearm muscle contraction and valgus motion. Shoulder absorbed energy by back muscle and forearm muscle contraction.

Table 1. Total energy absorbance for each different group.

	0 degree	10 degree	20 degree	30 degree
(Shoulder / Elbow)	5.49(0.64)	5.12(0.71)	5.37(0.68)	5.25(0.83)
(Shoulder / Wrist)	2.91(0.18)	2.73(0.23)	2.49(0.12)	3.05(0.31)

Table 2. Joint energy (N-m) during different period.

	0°	10°	20°	30°
wrist joint energy				
Ts to T1 period	1.5(0.3)	1.3(0.4)	1.8(0.4)	1.7(0.4)
Ts to T2 period	7.3(3.0)	8.4(3.1)	8.1(2.9)	8.9(3.0)
Ts to Te period	16.0(5.7)	17.8(5.6)	18.2(5.1)	16.9(5.9)
elbow joint energy				
Ts to T1 period	0.9(0.0)	1.1 (0.1)	1.0(0.2)	1.1(0.2)
Ts to T2 period	3.9(0.9)	4.2(0.9)	4.0(1.0)	4.3(0.9)
Ts to Te period	9.4(2.7)	9.1(2.4)	10.2(3.3)	9.9(3.1)
shoulder joint energy				
Ts to T1 period	2.5(0.6)	2.7(0.8)	2.1(0.6)	3.0(0.5)
Ts to T2 period	28.4(5.4)	30.4(6.1)	28.0(5.2)	31.1(6.0)
Ts to Te period	46.7(6.7)	48.7(6.4)	45.4(6.4)	50.7(6.0)

Unit : N-m "*" express $p < 0.05$

Table 3. Percentage of joint energy during different period.

	0°	10°	20°	30°
wrist joint				
T _s to T ₁ period	2.1(0.9)	1.7(0.5)	2.4(0.8)	2.2(0.9)
T ₁ to T ₂ period	7.9(1.8)	9.4(2.2)	8.6(1.6)	9.2(2.0)
T ₂ to T _e period	12.2(3.5)	12.5(3.8)	13.7(3.7)	10.2(3.1)
elbow joint				
T _s to T ₁ period	0.2(0.0)	2.0(0.7)	1.4(0.4)	1.4(0.4)
T ₁ to T ₂ period	4.1(1.4)	4.1(1.7)	4.0(1.2)	4.0(1.6)
T ₂ to T _e period	7.5(1.9)	6.5(2.0)	8.4(2.4)	7.1(2.0)
shoulder joint				
T _s to T ₁ period	3.5(1.3)	3.52(1.1)	2.9(1.0)	3.9(1.4)
T ₁ to T ₂ period	35.9(5.7)	36.6(5.2)	35.0(5.2)	35.7(5.8)
T ₂ to T _e period	25.4(3.7)	24.2(3.8)	23.5(3.1)	26.2(4.4)

unit : % total energy absorb "*" express $p < 0.05$

Table 4. Discomfort index.

groups	0 degree	10 degree	20 degree	30 degree
Uncomfortable index	4.9	5.4	5.7	6.3

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From the results of energy absorption, the shoulder joint would absorb the most of impact energy. Elbow joint absorbed much less energy than shoulder or wrist. During experiments process, the subject's knee have contacted the ground and absorbed some impact energy. Therefore, upper extremity joints were not significant difference among four groups in energy absorption and joint energy.

5. CONCLUSION

The experiments of different trunk tilting angles with 5cm fall height during fall on an outstretched hand were carried out in this study. The results showed that shoulder would absorb the most impact energy and followed by wrist and elbow. The time period at T₂ to T_e absorbed more energy in every joint.

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