EFFECT of FOREARM AXIALLY ROTATED POSTURE on
SHOULDER LOAD and SHOULDER ABDUCTION/FLEXION
ANGLES in FORWARD FALLS
前傾跌倒時前臂旋轉姿勢對肩關節負荷與外展和前舉角度之影響

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1. Abstract

Falling onto the outstretched hand is the most common cause of upper extremity injury. This study develops an experimental model for evaluating the shoulder load during a simulated forward fall onto one hand with three different forearm axially rotated postures, and examines the shoulder abduction angle and shoulder flexion angle in each case. In this study, fifteen healthy young male subjects with an average age of 23.7 years performed a series of one-armed arrests from a height of 5 cm onto a force plate. The kinematics and kinetics of the upper extremity were analyzed for three different forearm postures, namely 45° externally rotated (ER), non-rotated (NR), and 45° internally rotated (IR).

The shoulder joint load and shoulder abduction / flexion angles are significantly dependent on the rotational posture of the forearm. The shoulder medio-lateral shear forces in the ER group were found to be 1.83 and 2.94 times higher than those in the NR and IR groups, respectively. The shoulder flexion angles in the ER, NR and IR groups were 0.6°, 8.0° and 19.2°, respectively, while the corresponding shoulder abduction angles were 6.1°, 34.1° and 46.3°, respectively.

In falls onto the outstretched hand, an externally rotated forearm posture should be avoided in order to reduce the medio-lateral shear force acting on the shoulder joint. In falls of this type, a 45° internally rotated forearm posture represents the most effective fall strategy in terms of minimizing the risk of upper extremity injuries.

Keywords: Forward fall, Shoulder joint, kinematics, kinetics, Injury

中文摘要

前傾跌倒過程中，手肘過度伸展為主要造成上肢受傷的原因。本研究目的為了解在前傾跌倒過程中，不同前臂旋轉姿勢對肩關節負荷與外展和前舉角度影響之實驗模型。本實驗共邀請 15 位無任何上肢傷殘病史的男性受測者參與實驗計畫，其平均年齡為 23.7 歲。本實驗組別共分為三組：前臂外旋 45 度組、前臂無旋轉組與前臂內旋 45 度組。實驗結果發現，肩關節的負荷與前舉及外展角度會受前臂旋轉角度而影響，跌倒時，前臂外旋 45 度組其肩關節內外側剪力將會大於無旋轉組與前臂內旋 45 度組 1.83 倍與 2.94 倍。對於前臂外旋 45 度組、前臂無旋轉組與前臂內旋 45 度組之前舉角度為 0.6 度， 8.0 度和 19.2 度。對於前臂外旋 45 度組、前臂無旋轉組與前臂內旋 45 度組之外展角度為 6.1 度， 34.1 度和 46.3 度。本研究得知，前傾跌倒時當手肘過度伸展時應避免前臂外旋，進而使肩關節的內外側剪力能降低，避免肩關節受傷。本研究建議前臂內旋 45 度的跌倒策略是最有效降低上肢受傷的風險。

關鍵詞：前傾跌倒、肩關節、動力學、運動學、受傷

2. Introduction

Falling onto the outstretched hand is the most common cause of upper extremity injury. Fall-related shoulder injuries include acromio-clavicular joint dislocation, gleno-humeral joint dislocation, proximal humerus fracture, clavicle fracture, scapular fracture, rotator cuff tear, and superior labrum anterior to posterior lesion (SLAP) [1-3]. In order to prevent such injuries, it is necessary to fully understand the joint interaction mechanisms in the upper extremity, the force distribution within the shoulder joint, and the contributory effects of shoulder joint disorders.
Chou et al. [4] compared the elbow loads produced in simulated forward falls performed with elbow flexion and full extension, respectively. The results showed that the elbow valgus-varus shear force generated in the full extension falls was 68% larger (P=0.002) than that produced in the flexion falls. Performing elbow flexion at the moment of impact in forward falls reduces the magnitude of the initial peak impact force and postpones the occurrence of the second maximum peak. DeGoede and Ashton-Miller [5] investigated the effectiveness of various fall arrest strategies in minimizing the peak hand impact force during a forward fall. The results showed that the peak ground reaction force (GRF) applied to the distal forearm could be voluntarily reduced by flexing the elbow at the moment of impact. In other words, elbow flexion provides an effective damping mechanism which absorbs the impact energy in a forward fall and reduces the risk of upper extremity injury as a result [4, 6].

Lo and Ashton-Miller [7] investigated the effect of different lateral fall strategies on the impact force on the upper extremity. It was shown that the maximum force on the shoulder joint was produced when the fall was performed using a “Broomstick with Arm” strategy, in which the arm was used to break the fall first. Chou et al. [6] investigated the effect of various forearm axially rotated postures on the elbow load and the elbow flexion angle during simulated forward falls onto a one-armed arrest. The results showed that the elbow joint exhibited the largest elbow flexion angle (40.3°) and the minimum valgus-varus shear force (4.3% BW) when the forearm was externally rotated (ER) during the fall. Thus, it was inferred that an IR rotation of the forearm is beneficial in increasing the effectiveness of the damping mechanism produced by elbow flexion motion.

Although previous studies have demonstrated the effectiveness of the forearm IR posture in absorbing the impact energy in forward falls, little information is available regarding the effects of different forearm axially rotated postures on the shoulder joint load and flexion motion in forward falls onto an outstretched hand. Accordingly, this study develops an experimental model for evaluating the shoulder load during simulated forward falls onto a one-armed arrest with three different forearm axially rotated postures, and examines the range of the shoulder abduction motion and shoulder flexion motion in each case.

3. Methods
3.1 Subjects and Experimental Protocol
Fifteen male subjects volunteered to participate in the study. The subjects ranged from 22 to 27 years in age (mean 23.7, SD 1.79), 62 to 86kg in weight (mean 73.2, SD 7.0), and 163 to 183 cm in height (mean 173.7, SD 5.7). All of the subjects were right hand dominant and free of any musculoskeletal disorders of the upper extremity.

The subjects were asked to perform three one-armed falls, with each fall performed with a different forearm axially rotated posture, namely 45° externally rotated (ER); non-rotated (NR); and 45° internally rotated (IR). As shown in Figure 1, the subjects were dropped from a height of 5 cm (i.e. the distance between the outstretched hand and the force plate), and the subjects’ knees remained in contact with the ground at all times. The subjects were instructed to keep their elbow in full extension prior to impact. However, no specific instructions were given regarding the control of the upper extremity following the fall. In each test, the shoulder joint load and the shoulder abduction angle and shoulder flexion angle were recorded in order to test two null hypotheses, namely (1) the forearm rotation posture has no significant effect on the shoulder load in forward falls onto a one-handed arrest, and (2) the forearm rotation posture has no significant effect on the shoulder abduction / flexion motion in forward falls onto a one-handed arrest.

Prior to the tests, eleven reflective markers were placed on selected anatomic landmarks on each test subject. The landmarks were selected in accordance with rigid body assumptions for the 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), and hand (radial and ulnar styloid processes, third metacarpal bone). In addition, a triangular frame carrying three markers was placed on the upper arm in order to minimize the risk of measurement errors caused by a movement of the epicondyles skin during the fall. In analyzing the kinematics of the upper extremity, the center of the shoulder joint was defined as a point located at 90% along the length of an imaginary line drawn from the center of the elbow joint to the acromion marker [8]. In each test, the relative joint positions and the GRF were recorded using an ExpertVision motion system (Motion Analysis Corp., Santa Rosa, CA, USA) comprising six 120 Hz cameras and a 1000 Hz piezoelectric force plate (Type 9281B, Kistler Instrument Corp., Winterthur, Switzerland), respectively.

Each subject signed a consent-release agreement prior to performing the tests. In addition, the experiments were physically supervised by the author or one of the coauthors (each with a sports
medicine background) in order to avoid the risk of any accidental injuries.

3.2 Theorem and Governing Equations

In analyzing the elbow and shoulder joint forces under the different fall strategies, the upper extremity was modeled as a three-joint multi-linkage system comprising the hand, forearm, and upper arm. The free body diagrams of the three joints (i.e. the wrist, elbow and shoulder) are shown in Figure 2. The governing equations of the joint forces, moments and energies are derived in the following.

\[
\begin{align*}
\vec{F}_p &= m\ddot{a} - mg - \vec{F}_d \\
\vec{M}_p &= I\ddot{\alpha} - \vec{M}_d - (\vec{r}_p \times \vec{F}_p) - (\vec{r}_d \times \vec{F}_d) + \vec{\omega} \times (I \cdot \vec{\omega})
\end{align*}
\]

where
- \( \vec{F}_p \) proximal joint force.
- \( m\ddot{a} \) effective force.
- \( mg \) gravity force acting on local segment.
- \( \vec{F}_d \) distal joint force.
- \( m \) mass of segment.
- \( \vec{M}_p \) proximal joint moment.
- \( I \) mass moment of inertia.
- \( \vec{r}_p \) rotation matrix describing relative rotation between local coordinates of proximal segment and global coordinates.
- \( \vec{r}_d \) rotation matrix describing relative rotation between local coordinates of distal segment and global coordinates.
- \( \vec{\omega} \) angular velocity of local segment.

4. Results and Discussions

Previous experimental studies of one-armed arrests of a forward fall have generally focused on the effect of the forearm axially rotated posture on the load and flexion angle at the elbow. For example, Chou et al. [7] showed that a forearm IR posture achieved an effective reduction in the impact energy absorbed by the elbow joint. By contrast, the effects of the forearm rotation posture on the shoulder load and shoulder abduction / flexion angles in falls onto a single outstretched hand have received little attention. However, the results obtained in this study have shown that the shoulder load and the shoulder abduction / flexion angles are significantly dependent on the posture of the forearm at the moment of impact.

Chou et al. [7] investigated the elbow load and the ROM of the elbow flexion angle during simulated forward falls with three different axial rotations of the forearm. The results showed that the elbow flexion angle was 3.9° in the ER group, 24.6° in the NR group, and 40.3° in the IR group. In addition, the elbow valgus-varus shear force in the ER group was found to be 1.4 times higher than that in the NR group and 2.7 times higher than that in the IR group. In other words, the IR posture of the forearm yielded the highest value of the elbow flexion angle and the lowest value of the valgus-varus shear force (4.3% BW). In the present study (Figure 3), the shoulder flexion angle was found to have a value of 0.6° in the ER group, 8.0° in the NR group, and 19.2° in the IR group. Meanwhile, the shoulder abduction angle was found to be 6.1° in the ER group, 34.1° in the NR group, and 46.3° in the IR group. In addition (see the Table 1), the shoulder medio-lateral shear force in the ER group was 1.83 times higher than that in the NR group and 2.94 times higher than that in the IR group. In other words, the effects of the forearm axially rotated posture on the shoulder load and shoulder abduction / flexion angles are similar to those of the forearm rotation posture on the elbow load and elbow flexion angle. Specifically, the present results show that an internally-rotated posture of the forearm results in significantly higher abduction and flexion angles at the shoulder and a significantly lower medio-lateral shear stress. In the forearm IR posture, the shoulder joint is able to perform abduction and flexion motion during the impact phase of the fall with relative ease. This motion provides a damping function, and therefore reduces the energy absorbed by the shoulder joint during impact.

Chou et al. [7] reported that in falls onto an outstretched hand, an ER posture of the forearm may cause the elbow to lock in full extension under impact. The results obtained in this study show that a forearm ER posture severely limits the ROM of the shoulder joint during arrested falls onto a single, outstretched hand. As a consequence, the loading on the shoulder joint increases, causing a corresponding increase in the risk of shoulder injury.

5. Conclusion

This study has investigated the effect of the forearm axially rotated posture on the shoulder load and shoulder abduction / flexion angles in forward falls onto a single outstretched hand. The results show that the forearm IR posture enables the shoulder joint to perform a greater flexion motion during the impact phase of the fall, thereby increasing the absorption of the impact energy and
reducing the risk of shoulder injury.

The results obtained in this study have shown that the forearm IR posture yields a significant reduction in the shoulder medio-lateral shear stress and a significant increase in the shoulder abduction / flexion angles. These findings are consistent with the results presented by Chou et al. [7] for the effects of the forearm IR posture on the flexion motion and loading force at the elbow in one-armed arrests of a forward fall. Thus, it can be inferred that the forearm IR posture leads to a beneficial damping effect at both the shoulder joint and the elbow joint during forward falls onto a single hand, and therefore represents the most effective fall strategy in terms of minimizing the risk of upper extremity injuries.

Acknowledgements

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6. Reference


Figure 2. Segmental free body diagram.

Figure 3. Effect of forearm axially rotated posture (angle) on mean (SD) shoulder abduction angle and shoulder flexion angle. Bars represent SD. (****: P<0.01)

Table 1. Mean (SD) calculated shoulder joint force (as % of BW) for three different forearm rotational postures.

<table>
<thead>
<tr>
<th>Variables</th>
<th>ER</th>
<th>NR</th>
<th>IR</th>
<th>P</th>
<th>Post-hoc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antero-posterior</td>
<td>21.0</td>
<td>21.5</td>
<td>24.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(X axis)</td>
<td>(6.7)</td>
<td>(5.5)</td>
<td>(7.8)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medio-lateral</td>
<td>23.5</td>
<td>14.6</td>
<td>8.0</td>
<td>*</td>
<td>ER&gt;NR</td>
</tr>
<tr>
<td>(Y axis)</td>
<td>(6.3)</td>
<td>(5.3)</td>
<td>(4.9)</td>
<td>&gt;IR</td>
<td></td>
</tr>
<tr>
<td>Axial Forces</td>
<td>56.0</td>
<td>53.0</td>
<td>50.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Z axis)</td>
<td>(11.2)</td>
<td>(9.8)</td>
<td>(20.0)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Unit: (% body weight); BW: body weight.
# P value is significance of one-way ANOVA.
* P < 0.01.