Effects of Fatigue on Stability of Upper Extremity During Bench-press Exercise

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Abstract

This study explores the effect of exercise-induced fatigue on upper extremity stability. The kinematic changes of the upper extremity during bench-press exercise are quantified by measuring the flexion angle and range of motion of the elbow joint, the amplitude of the pitch angle, the amplitude of the yaw angle, and the perturbation frequencies of the pitch and yaw angles, respectively. Fifteen healthy males performed bench presses until fatigue set in. The joint kinematics in the initial stage and the fatigue stage of the bench-press exercise are calculated and analyzed using a laboratory-developed three-dimensional motion analysis system. The flexion angle and range of motion of the elbow joint are significantly higher in the initial stage of the bench-press exercise than in the fatigue stage. The amplitude of the pitch angle in the fatigue stage (mean 11.98°, standard deviation (SD) 3.52°) is significantly higher than that in the initial stage (mean 2.85°, SD 1.13°). The amplitude of the yaw angle in the fatigue stage (mean 8.87°, SD 2.05°) is significantly higher than that in the initial stage (mean 3.27°, SD 1.70°). Finally, the perturbation frequencies of the pitch and yaw angles, respectively, are both significantly higher in the fatigue stage than in the initial stage. The results provide useful insight into the relationship between fatigue-induced perturbation frequency and the instability of the upper extremity during bench-press exercise. An unstable upper extremity posture may increase the risk of injury during the fatigue stage of repetitive exercise.

Keywords: Upper extremity, Bench press, Fatigue, Perturbation frequency, stability

1. Introduction

Fatigue has a critical effect on an individual’s physical performance and can result in various forms of musculoskeletal injury. Many researchers have investigated the effects of fatigue on the kinematics of the lower extremity during various physical exercises [1-4]. In general, the results have shown that fatigue leads to reduced knee proprioception, increased joint laxity, a diminished capacity for rapid shock absorption, and delayed muscular activation. In contrast, the effects of exercise-induced fatigue on the upper extremity have attracted relatively little attention. However, several researchers have reported that functional fatigue affects the acuity of the performance of the whole upper extremity in throwing tasks [5-7]. In addition, it has been shown that the kinematic and positional sense changes of the upper extremity joints following functional fatigue protocols, indicating a decrease in proprioceptive sense with muscle fatigue, may play a role in decreasing athletic performance and in fatigue-related shoulder dysfunction [8].

Sparto et al. [9] reported that the significant reduction in postural stability caused by repetitive lifting tasks leads to a higher risk of injury in the presence of unexpected perturbations. Bench-press exercise notably improves the muscular strength and stamina of the upper extremity. However, during prolonged bench-press exercise, fatigue causes the movement time to increase and the exercise speed to decrease [10,11]. Thus, to maximize the effectiveness of bench-press protocols while simultaneously minimizing the risk of physical injury, it is essential to clarify the relationship between fatigue and the stability of the upper extremity.

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Various biomechanical models of the upper extremity have been proposed for investigating kinematic parameters under simulated fall conditions or in upper-extremity training exercises [12-16]. These models have proven useful in investigating potential injury mechanisms in the event of a fall onto an outstretched hand. However, they have not been applied to specifically examine the effects of fatigue on the joint variables during upper-extremity exercises. Recent studies have utilized one-repetition maximum (1RM) tests to measure the upper-extremity muscular strength in basic lift exercises such as bench presses by evaluating the maximum weight which can be lifted successfully through the full range of motion [17-20]. Knoll et al. presented several predictive equations based on the number of repetition cycles required for fatigue to set in for evaluating upper-extremity muscular strength [21]. In general, a strong correlation exists between the 1RM value and the number of repetitions for 10 or fewer repetitions. However, the exact 1RM value depends on both the gender and the training history of the participant [22].

The present study examines the effects of fatigue on the stability of the upper extremity during bench-press exercise. The kinematic changes of the upper extremity during bench-press exercise are quantified by measuring the flexion angle and range of motion of the elbow joint, the amplitude of the pitch angle (APA), the amplitude of the yaw angle (AYA), and the perturbation frequencies of the pitch and yaw angles, respectively.

2. Materials and methods

2.1 Instruments

The motion trajectories of the upper extremity were recorded with a sampling frequency of 60 Hz using a three-dimensional (3D) optical motion capture system (Eagle Digital System, Motion Analysis Corporation, Santa Rosa, CA, USA). The system comprised eight Eagle Digital Cameras, an Eagle Hub, and EVaRT software to acquire and post-process the experimental data.

2.2 Participants and experimental procedures

Fifteen healthy weight-lifting males (mean age: 19.6 ± 0.8 years old; mean weight: 69.6 ± 8.6 kg; mean height: 168.7 ± 5.5 cm) volunteered to take part in the study. A 19-kg weight was used to ensure identical loading conditions during the bench-press exercise. None of the subjects had any previous history of upper extremity injuries or disorders.

The participants were asked to begin the bench-press exercise in the “up” state. A bench-press cycle involved lowering the barbell to the “down” state and then returning it to the “up” state (Fig. 1). The subjects were asked to repeat the cycle continuously until they were physically unable to perform any more repetitions.

For each participant, reflective markers were placed on selected bony anatomical landmarks. The trajectories of these landmarks were recorded using the motion analysis system. The landmarks were chosen in accordance with rigid body assumptions for the trunk (cervical vertebra 7, thoracic vertebra 4, and acromion processes), upper arm (acromion process and medial and lateral epicondyles of the elbow), forearm (medial and lateral epicondyles of the elbow and ulnar styloid processes), and hand (radial and ulnar styloid processes and third metacarpal bone) (Fig. 2). In addition, three markers were attached to a triangular frame and placed on the upper arm in order to minimize errors caused by movement of skin over epicondyle during the bench-press repetitions. The center of the shoulder joint was defined as the point located at 90% of the way along an imaginary line drawn from the elbow joint center (as calculated from the medial and lateral markers) to the acromion marker.

Figure 1. Photographs showing (a) “up” state and (b) “down” state in bench-press cycle.

2.3 Data processing and analysis

The aim of the experiments was to analyze the stability of the upper extremity in the initial stage (IS) and the fatigue stage (FS) of the bench-press exercise. For convenience, the IS and FS were defined as the first and last three cycles of a test run, respectively. For each stage, the three sets of kinematic measurements obtained in the “up-to-down” and “down-to-up” phases of the bench-press cycle were averaged to obtain a mean

![Figure 2. Diagram of reflective markers on bony anatomical landmarks.](image-url)
measurement value for further analysis.

The kinematic changes of the upper extremity over the course of the bench-press exercise were quantified by measuring the flexion angle and range of motion of the elbow joint, the amplitude of pitch angle (APA), the amplitude of yaw angle (AYA), and the perturbation frequencies of the pitch and yaw angles, respectively. As shown in Fig. 3, the APA is defined as the change in the angle of rotation of the barbell about the I axis, where the I-J horizontal plane is defined as zero-degree rotation. Similarly, the AYA is defined as the change in the angle of rotation of the barbell about the K axis, where the vertical J-K plane is defined as zero-degree rotation. The APA and AYA data were plotted in the form of time-based curves, and the perturbation frequency was then calculated as the number of peaks per cycle in the portion of the curve.

Figure 3. (a) Definition of APA; (b) definition of AYA; and (c) coordinate system used to describe motion trajectories during bench-press exercise. I, J, and K denote three orthogonal unit vectors. L, R, and C markers on the barbell denote the left-hand side, the right-hand side, and the center of the barbell, respectively.

The joint kinematics of the upper extremity were calculated using proprietary kinematic and MATLAB programs. Each segment of the upper-extremity was assumed to be a rigid body. In addition, the 3D orientations of the joint movements were calculated using Euler’s method with a y-x’-z” rotational sequence via the marker-based coordinate system.

### 2.4 Statistical analysis

The experimental data were analyzed using commercial SPSS statistical analysis software (SPSS Inc., Chicago, IL, USA). In addition, a paired t-test with a 95% confidence interval was performed to compare the values of the kinematic parameters obtained in the IS of the exercise with those obtained in the FS.

### 3. Results

This section presents the major results obtained for the kinematic parameters of the upper extremity during the IS and FS of the bench-press exercise.

As shown in Table 1, in the “down” state of the bench-press cycle, the mean flexion/extension angle of the elbow was significantly smaller in the FS (mean 99.1°, standard deviation (SD) 10.33°) than in the IS (mean 105.01°, SD 10.9°). In the “up” state, no significant difference exists between the mean flexion/extension angles in the IS and FS, respectively. However, a significant difference exists in the range of motion of the elbow joint between the FS (mean 79.29°, SD 9.07°) and the IS (mean 85.4°, SD 10.6°). Overall, the results show that fatigue has a significant effect on the kinematic response of the elbow joint.

Table 1. Elbow joint angle and elbow range of motion during initial stage and fatigue stage of continuous bench-press exercise.

<table>
<thead>
<tr>
<th>Elbow</th>
<th>Initial Stage (IS)</th>
<th>Fatigue Stage (FS)</th>
<th>t-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexion(+) /</td>
<td>Mean (SD)</td>
<td>Mean (SD)</td>
<td>P*</td>
</tr>
<tr>
<td>Down</td>
<td>19.62 (11.57)</td>
<td>18.27 (7.74)</td>
<td>0.43</td>
</tr>
<tr>
<td>Up</td>
<td>105.01 (10.9)</td>
<td>99.10 (10.33)</td>
<td>0.01* IS &gt; FS</td>
</tr>
<tr>
<td>Range of motion</td>
<td>85.40 (10.6)</td>
<td>79.29 (9.07)</td>
<td>0.01* IS &gt; FS</td>
</tr>
</tbody>
</table>

P value is significant (p < 0.05) between initial and fatigue stages as obtained using the paired t-test.

As shown in Table 2, the APA in the FS (mean 11.98°, SD 3.52°) was significantly higher than that in the IS (mean 2.85°, SD 1.13°). The pitching perturbation frequency (PPF) in the “up-to-down” portion of the cycle was significantly higher in the FS (mean 8.8, SD 0.7) than in the IS (mean 5.4, SD 0.6). Similarly, the PPF in the “down-to-up” portion of the cycle was significantly higher in the FS (mean 9.5, SD 0.9) than in the IS (mean 6.1, SD 0.5).

Table 2. Amplitude of pitch angle (APA) and pitching perturbation frequency (PPF) during initial stage and fatigue stage of continuous bench-press exercise.

<table>
<thead>
<tr>
<th>Pitching motion</th>
<th>Initial Stage (IS)</th>
<th>Fatigue Stage (FS)</th>
<th>P*</th>
</tr>
</thead>
<tbody>
<tr>
<td>APA (degrees)</td>
<td>Mean (SD)</td>
<td>Mean (SD)</td>
<td>P*</td>
</tr>
<tr>
<td>Descending</td>
<td>5.4 (0.6)</td>
<td>8.8 (0.7)</td>
<td>0.01* IS &gt; FS</td>
</tr>
<tr>
<td>Ascending</td>
<td>6.1 (0.5)</td>
<td>9.5 (0.9)</td>
<td>0.01* IS &gt; FS</td>
</tr>
</tbody>
</table>

P value is significant (p < 0.05) between initial and fatigue stages as obtained using the paired t-test.

As shown in Table 3, the AYA in the FS (mean 8.87°, SD 2.05°) was significantly higher than that in the IS (mean 3.27°, SD 1.70°). The yawing perturbation frequency (YPF) in the “up-to-down” portion of the cycle was significantly higher in the FS (mean 49.4, SD 8.6) than in the IS (mean 25.5, SD 8.2). Similarly, the YPF in the “down-to-up” portion of the cycle was significantly higher in the FS (mean 54.5, SD 5.2) than in the IS (mean 31.3, SD 5.50).
The average number of cycles required for fatigue to set in was 20.5 (SD 4.55).

4. Discussion

The results presented in Tables 1-3 suggest that a loss in stability of the upper extremity occurs during the FS of bench-press exercise. This loss in stability may be due to fatigue inducing unexpected perturbations in the joint kinematics of the upper extremity [9].

In 3D Euclidean space, the reference orientations of a rigid body are usually described using three independent Euler angles [23]. The barbell used in the present experiments can be regarded as a slender body [24-26]. Hence, the three-axis conventions and notations used to describe the movement of traditional slender bodies such as aircraft, missiles, and sea-going vessels can be used to describe the motion of the barbell during each cycle of the bench-press exercise. Conventionally, the axes used to describe the motion of an aircraft, missile, or ship are referred to as the vertical, lateral, and longitudinal axes. The rotations of the slender body around these axes are defined as yaw, pitch, and roll, respectively [26].

A dynamic system is said to be stable if it tends to return to and remain in an equilibrium state when slightly disturbed from this state via an external force or displacement [24]. In this study, the state of equilibrium is described using roll, pitch, and yaw. Thus, the stability of the barbell was evaluated using the parameters APA, AYA, PPF, and YPF, with the assumption that the stability of the barbell was representative of the stability of the upper extremity.

In general, the experimental results obtained in this study show that fatigue has a critical effect on both the elbow joint angle and the stability of the upper extremity during bench-press exercise. In the bench-press experiments, the subjects were asked to perform repetitions until they were physically unable to perform any more. This condition is very similar to that applied in 1RM tests, which measure muscular strength in terms of the maximum weight which the subject can successfully lift through the full range of motion. The significant difference observed in the elbow joint angles in the IS and FS of the bench-press exercise confirms that fatigue has a major effect on the multi-joint kinematics of the upper extremity. For both the IS and the FS, the values of the elbow joint angles in the “down” state of the bench-press cycle are consistent with a previous study by the current group, which found that the peak flexion angle of the elbow during bench-press exercise is around 90-100 [27]. The upper extremity can be regarded as a simple three-linkage system, comprising the hand, forearm, and upper arm. At the start of the bench-press cycle, the upper extremity forms a vertical pillar which supports the barbell in the “up” position. As the barbell moves to the “down” position, the flexion of the upper extremity induces medial and posterior stress. Fatigue affects not only the elbow angle, but also the stability of the upper extremity, as quantified by the APA, AYA, PPF, and YPF parameters. Sparto et al. [9] suggested that the occurrence of sudden unexpected perturbations of kinematic trajectories during repetitive exercises may lead to an increased risk of physical injury. Thus, in designing bench-press exercise protocols, reliable means of quantifying the perturbations in the motion trajectories of the upper body are required in order to minimize the risk of injury.

This study provides the first reported analysis of upper-extremity stability during bench-press exercise using yaw and pitch perturbation frequencies, and the first direct comparison of the APA, AYA, PPF, and YPF parameters in the initial and fatigue stages of the bench-press exercise. The results confirm that fatigue leads to a significant reduction in the elbow angle and a significant increase in the APA, AYA, and associated perturbation frequency parameters. Overall, the results suggest that fatigue causes a loss in upper-extremity stability during prolonged bench-press exercise.

The present results extend the findings of previous studies regarding repetition-related differences in the ability of different subjects to sustain a high level of performance when engaged in exercises involving the upper extremity. For example, some studies have shown a post-fatigue performance reduction, while others have found that some individuals maintain the ability to accurately hit a target even when fatigued [28,29]. The apparent discrepancy in the two sets of findings may be explained by the redundancy of the human body, which enables very similar tasks to be performed using different muscle combinations.

The barbell weight determines the onset of muscle fatigue. In order to minimize the risk of exercise-related injury, a 19-kg barbell, which provides a loading that is similar to that during a push up, was used in this study. Sparto et al. [9] developed several biomechanical models to investigate the kinematic effects of fatigue during repetitive lifting exercises. The present study examined the effects of fatigue on the upper-extremity kinematics from an instability perspective. The experimental results show that fatigue has a significant effect on the multi-joint kinematics of the upper extremity during bench-press exercise. The perturbation frequency results presented in Tables 2 and 3 indicate that fatigue reduces the ability of the subject to control the motion trajectories of the upper extremities, leading to instability. As discussed in [9], the occurrence of unexpected perturbations in the joint kinematics during the performance of repetition-based exercises increases the risk of physical injury due to the corresponding unexpected perturbation of the joint forces. Specifically, the joint forces increase with increasing perturbation frequency. The present results show that the perturbation frequency increases

### Table 3. Amplitude of yaw angle (AYA) and yawing perturbation frequency (YPF) during initial stage and fatigue stage of continuous bench-press exercise.

<table>
<thead>
<tr>
<th>Yawing motion</th>
<th>Initial Stage (IS)</th>
<th>Fatigue Stage (FS)</th>
<th>P’</th>
</tr>
</thead>
<tbody>
<tr>
<td>AYA (degrees)</td>
<td>Mean (SD)</td>
<td>Mean (SD)</td>
<td></td>
</tr>
<tr>
<td>Descending</td>
<td>25.5 (8.2)</td>
<td>49.4 (8.6)</td>
<td>0.01*</td>
</tr>
<tr>
<td>(per cycle)</td>
<td></td>
<td></td>
<td>IS &gt; FS</td>
</tr>
<tr>
<td>Ascending</td>
<td>31.3 (5.5)</td>
<td>54.5 (5.2)</td>
<td>0.01*</td>
</tr>
<tr>
<td>(per cycle)</td>
<td></td>
<td></td>
<td>IS &gt; FS</td>
</tr>
</tbody>
</table>

*P value is significant (p < 0.05) between initial and fatigue stages as obtained using the paired t-test.
significantly as the subject approaches the point of fatigue. In other words, the risk of physical injury increases as the subject tires. Thus, in designing any bench-press-related exercise protocol, the number of repetitions should be carefully controlled in accordance with training history of the participant.

This study had several limitations. The perturbation frequency was examined in only two directions (pitch and yaw). However, in practice, the stability of the upper extremity is governed by a complex combination of muscles and joints. Another limitation is the lack of information regarding muscle power. Thus, while the present results provide useful insight into the effects of fatigue on unexpected perturbation frequency and upper extremity stability, a future study should develop a more sophisticated model to describe the effects of exercise-induced fatigue on the stability of the upper extremity.

5. Conclusion

This study investigated the effects of fatigue on the stability of the upper extremity during bench-press exercise. The results show that the amplitude of the pitch angle in the fatigue stage is significantly higher than that in the initial stage. Similarly, the amplitude of the yaw angle in the FS is significantly higher than that in the IS. Finally, the perturbation frequencies of the APA and AYA responses, respectively, are significantly higher in the FS than in the IS. Previous studies have suggested that the risk of physical injury increases with increasing frequency of unexpected perturbations in the motion trajectories of the upper extremities. Thus, the present results suggest that bench-press repetitions should be terminated before the stage of complete fatigue.

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References


