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original research

Recovery of Upper Extremity Sensorimotor System Acuity in Baseball Athletes After a Throwing-Fatigue Protocol

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Context: Research indicates that upper extremity fatigue hampers sensorimotor system acuity. However, no investigators have observed recovery of upper extremity acuity after fatigue.

Objective: To observe recovery of active position reproduction acuity in overhead throwers after a throwing-fatigue protocol.

Design: Single-session, repeated-measures design.

Setting: University musculoskeletal laboratory.

Patients or Other Participants: Sixteen healthy collegiate baseball players (age = 21.0 ± 1.6 years, height = 175.8 ± 10.2 cm, mass = 82.8 ± 4.3 kg).

Intervention(s): Subjects threw a baseball with maximum velocity (every 5 seconds) from a single knee. Every 20 throws, subjects rated their upper extremity exertion on a Borg scale until reporting a level of more than 14.

Main Outcome Measure(s): We used an electromagnetic tracking system to measure active multijoint position reproduction acuity at 5 intervals: prefatigue; immediately postfatigue; and after 4, 7, and 10 minutes of recovery. Blindfolded subjects reproduced their arm-cocked and ball-release positions. Dependent variables were 3-dimensional variable errors of scapulothoracic, glenohumeral, elbow, and wrist joints; endpoint (ie, hand) position error represented overall upper extremity acuity. The independent variable was time (measured prefatigue and at 4 postfatigue intervals).

Results: Fatigue significantly affected acuity of scapulothoracic, glenohumeral, and elbow joints and endpoint error for both positions ($P < .001$). Fatigue significantly affected wrist acuity only for ball release ($P < .001$). For arm-cocked reproduction, each measure of acuity, except that of the glenohumeral joint, recovered by 7 minutes; for ball release, each measure of acuity recovered within 4 minutes ($P > .05$).

Conclusions: The sensorimotor system deficits that we observed after fatigue recovered within 7 minutes in most upper extremity joints. Glenohumeral arm-cocked position reproduction acuity failed to recover within 10 minutes. Research indicates that overhead throwers are vulnerable in this position to the capsulolabral injuries commonly observed in throwing athletes. Future researchers should explore this relationship and the effectiveness of exercises aimed at enhancing sensorimotor system acuity and endurance.

Key Words: multijoint position reproduction, joint position sense

Key Points

- Our fatigue protocol affected sensorimotor system acuity, causing significantly greater error in each measure of acuity except wrist acuity at the arm-cocked position.
- Failure of the glenohumeral joint to recover after 10 minutes may reflect the greater relative demands placed on arm accelerators during our throwing-fatigue protocol.
- Clinicians should allow a minimum of 4 to 7 minutes for recovery between fatiguing bouts of throwing to avoid accumulation of sensorimotor system deficits.
- Rehabilitation and conditioning activities for throwers should include multijoint upper extremity exercises that address sensorimotor system acuity and endurance.

Overhead throwing is a dynamic and complex activity that creates and transfers large-magnitude forces through the upper extremity.[1–3] These forces must be controlled efficiently through proper throwing mechanics to maximize performance and to help avoid injury.[4] The responsibility of maintaining throwing form and dynamic stability falls on the sensorimotor system (SMS).[5,6] However, evidence suggests that injury[7] and fatigue[8–11] compromise SMS function in the upper extremity. In research specific to overhead throwers, authors further suggested that a throwing-fatigue protocol decreases SMS acuity[12] and prolonged throwing alters pitching mechanics.[13] Such compromise of this system via injury or fatigue hampers neuromuscular control, which may result in greater-magnitude forces imparted on upper extremity joints and eventually may increase risk of further injury.[5,14]

Researchers[8–10] have established many of the immediate effects that upper extremity fatigue has on SMS acuity, but the rate of recovery is less clear. Through measures of balance, investigators[15–17] have observed recovery of SMS function after lower extremity fatigue protocols. Results suggest that balance recovers within as little as 75 seconds after highly intense fatigue protocols.[15] Recovery may take as long as 15 minutes after less-intense fatigue protocols that require as long as 25 minutes of exercise to complete.[16,17] However, little evidence describing recovery of SMS function in the upper extremity after functional fatigue exists. Therefore, our purpose was to observe recovery of upper extremity SMS acuity in overhead throwers after a functional-fatigue protocol through active multijoint (wrist, elbow, glenohumeral, and scapulothoracic) reproduction of 2 functional positions. Because of the intensity of our fatigue protocol ($<$12 minutes), we hypothesized that upper extremity SMS acuity would recover within 10 minutes in a manner similar to balance measures.

METHODS

Subjects

Sixteen healthy collegiate baseball players (age = 21.0 ± 1.6 years, height = 175.8 ± 10.2 cm, mass = 82.8 ± 4.3 kg) volunteered for this study. Subjects reported 2.3 ± 1.2 years of experience in National Collegiate Athletic Association baseball and included 6 pitchers, 5 infielders, and 5 outfielders. Fourteen subjects were right-handed throwers, and 2 were left-handed throwers. No volunteers reported a history of upper extremity injury or surgery or central nervous system disorders. All testing took place during the off-season in November and December. We explained the testing procedures, and volunteers signed an informed consent form. The university's institutional review board approved this study.

Procedures

All subjects reported to the University Musculoskeletal Research Laboratory for testing. We used a single-session, repeated-measures design. Data used in this study were collected as one component of a larger research project in which we observed the effects of functional fatigue on upper extremity SMS acuity. We examined the immediate effects of fatigue on each plane of motion and upper extremity joint in a separate report.[18] Unique to this study are the recovery values.

We used a Flock of Birds electromagnetic tracking device (Ascension Technology, Burlington, VT) with MotionMonitor software (Innovative Sports Training, Chicago, IL) to measure acuity of active multijoint position reproduction (AMPR). We collected data at 100 Hz and used a fourth-order, zero-phase-shift Butterworth filter (20-Hz cutoff) to smooth positional and angular data.

We attached electromagnetic sensors to the subject's sternum and hand, forearm, humerus, and scapula of the throwing arm. Double-backed tape and Cover-Roll (Beiersdorf Inc, Norwalk, CT) held sensors to the posterior acromial angle of the scapula, just inferior to the sternal notch, and to the dorsal surface of the third metacarpal. We used elastic cuffs and Tuf-Skin (Cramer Products Inc, Gardner, KS) to secure sensors to the distal radius and lateral humerus. We used elastic cuffs and a belt to stabilize cords from distal sensors to limit sensory feedback from the cords.

Next, we asked subjects to warm up normally, throwing and stretching until they were comfortable throwing at maximum velocity. Using a wooden stylus to identify bony landmarks, we then digitized subjects, creating local and then anatomically relevant coordinate systems for the thorax and each involved segment.

We followed the International Society of Biomechanics' standard protocol[19] and Euler rotation sequences for upper extremity kinematic analysis. This method is a valid[20] measure of scapular and humeral motion.

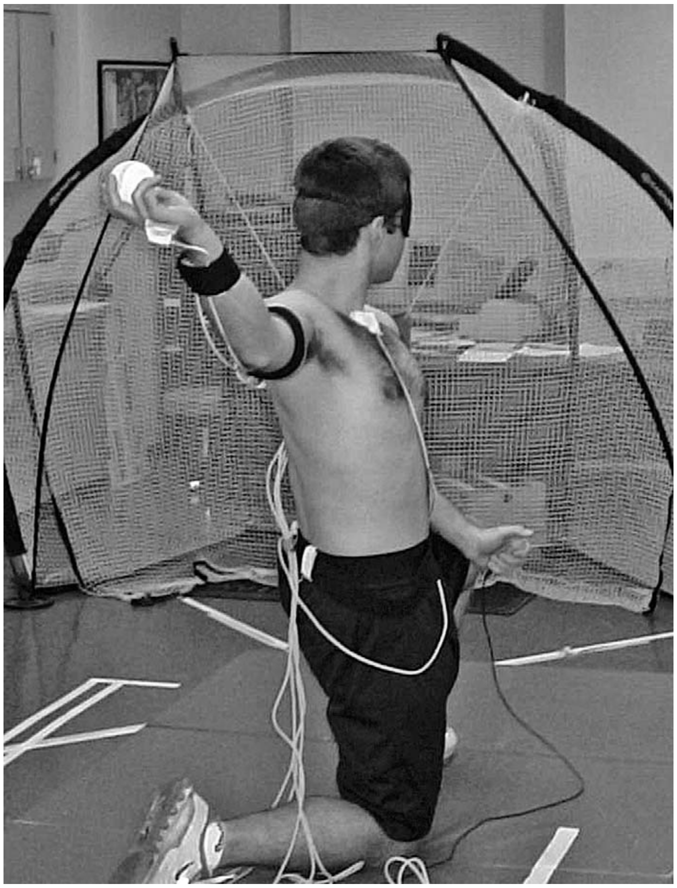

Figure 1. An overhead throwing athlete reproduces his arm-cocked position during the active multijoint position reproduction test. Reprinted with permission.[18]

Active Multijoint Position Reproduction

We followed the previously described AMPR testing procedures.[21,22] Subjects knelt with the hip of the nondominant side flexed to 90° and foot flat on the ground. We chose this position to assure a standard and appropriate distance between subjects and the electromagnetic transmitter and to expedite fatigue by limiting contribution of force from the lower extremity during throwing.

We tested subjects' ability to reproduce their arm-cocked (Figure 1) and ball-release (Figure 2) positions. To control for biasing of test sequence, we counterbalanced the order of the 2 test positions. We blindfolded subjects for a target trial and 3 repositioning trials. During identification of the initial target trial, we instructed subjects to ''recreate this position'' during the 3 trials that were to follow. We gave these specific instructions to avoid creating bias toward any one joint and to ensure each subject's conscious appreciation of the target position. Orientation of each upper extremity joint during this initial trial served as the subject's target position for the 3 repositioning trials to follow. We used these clinical joint angles (ie, orientation of distal segments with reference to proximal segment) as target angles for calculating angular error for subsequent repositioning trials. We asked the subjects to actively go through the throwing motion and to pause, holding each

Figure 2. An overhead throwing athlete reproduces his ball-release position during the active multijoint position reproduction test. Reprinted with permission.[18]

position for 1 to 2 seconds while depressing a trigger in their nonthrowing hand when they believed they had recreated the target position. Subjects identified each position 4 times (1 target and 3 repositioning trials). They remained blindfolded between trials, each beginning within 5 seconds of the previous trial. The time between identification of a target position and completion of all repositioning trials did not exceed 20 seconds. We did not provide results or feedback regarding acuity of individual trials at any time.

Functional Fatigue Protocol

Before starting the fatigue protocol, we provided subjects with written and oral instructions for using the Borg Rating of Perceived Exertion (RPE) scale.[23] Subjects used scale ratings of 6 to 20 to indicate the level of ''local'' exertion or fatigue in their throwing arm every 20 throws throughout the throwing protocol. This scale is a valid measure of local upper extremity exertion.[24,25]

We used a previously described standardized throwing-fatigue protocol.[12] Subjects knelt as described for AMPR testing and participated in a single bout of throwing baseballs (Rawlings Sporting Goods Co Inc, St Louis, MO; circumference = 22.86 cm [9 in], mass = 0.16 kg [5 oz]) at a 14.18-cm (17-in) target that was located 6.10 m (20 ft) away. We asked subjects to throw with maximum velocity and accuracy when prompted by a computerized audible command (every 5 seconds). To measure ball velocity, we used a radar gun (JUGS Pitching Machine Company, Tualatin, OR) with a reported accuracy of ±0.5 mph (±0.22 m/s). We allowed each subject 3 to 5 throws to become familiar with the procedures and used the maximal velocity of these throws as his goal velocity. To encourage maximal effort, we warned participants if the velocity fell to less than 90% of their goal.

We considered each subject fatigued and discontinued the fatigue protocol when he reported a level of exertion exceeding 14 or after 160 throws. Subjects were not aware of the threshold used to discontinue the fatigue protocol.

Immediately after the throwing protocol, we retested participants in the same manner as prefatigue measures. We measured AMPR acuity for each position 4 times during the 10 minutes after the fatigue protocol: within 1 minute after the fatigue protocol (postfatigue) and at 4 minutes, 7 minutes, and 10 minutes of recovery.

Data Reduction

We exported angular and position data from the MotionMonitor (Innovative Sports Training) into Microsoft Excel (version 2000; Microsoft Corp, Redmond, WA) to calculate error scores. We calculated separate 3-dimensional variable error scores (3DVE) to quantify acuity of each joint (scapulothoracic, glenohumeral, elbow, and wrist) and for each test position (arm cock and ball release) in the same manner as in previous investigations,[12,21,22] using the global standard deviation of end-position dispersions.[26] Each joint's 3DVE calculation incorporates error from each motion measured at the individual joint. Using angular data, we calculated deviation (in degrees) between the target orientation and that of each repositioning trial in 3 motions at the scapulothoracic (internal-external rotation, upward-downward rotation, and posterior-anterior tilt) and glenohumeral (internal-external rotation, horizontal abduction-adduction, and flexion-extension) joints and 2 motions at the elbow (pronation-supination and flexion-extension) and wrist (ulnar-radial deviation and flexion-extension).

We also calculated separate 3DVE scores to represent acuity of the entire upper extremity for reproduction of each test position. The SMS uses position of the hand in relation to the thorax as the goal for planning upper extremity tasks.[27,28] Therefore, we calculated the 3-dimensional deviation of endpoint (ie, hand) position in relation to the thorax (in millimeters) to quantify overall acuity of the upper extremity for each test position.

Statistical Analysis

For each test position, we compared 3DVE scores over time for each joint (scapulothoracic, glenohumeral, elbow, and

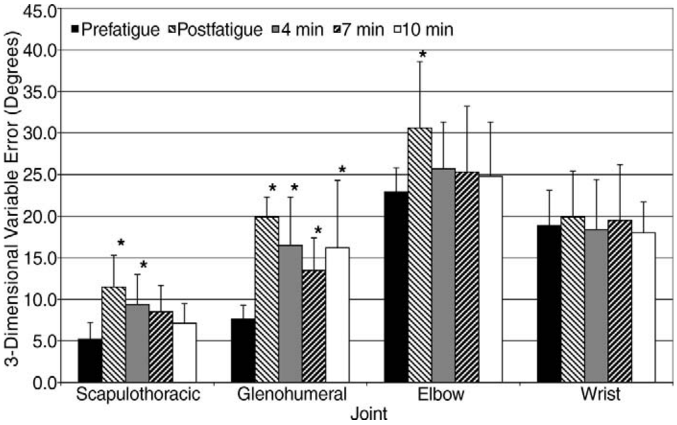

Figure 3. Analysis for recovery of individual upper extremity joint acuity (3-dimensional variable error [mean ± SD]) for arm-cocked position reproduction after the throwing-fatigue protocol. Comparisons of prefatigue with postfatigue and each recovery test are presented. *Indicates significantly greater error than the respective joint's prefatigue value ($P < .001$).

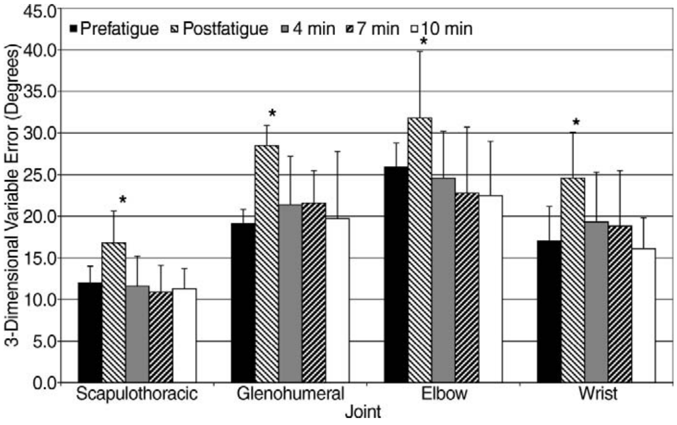

Figure 4. Analysis for recovery of individual upper extremity joint acuity (3-dimensional variable error [mean ± SD]) for ball-release position reproduction after the throwing-fatigue protocol. Comparisons of prefatigue with postfatigue and each recovery test are presented. *Indicates significantly greater error than the respective joint's prefatigue value ($P < .001$).

wrist) and endpoint position. Because 56% of the variables violated the assumption of normality and 22% violated the assumption of homogeneity of variances, nonparametric tests were appropriate. We used a Friedman test (repeated-measures analysis of variance by ranks) to observe differences in acuity over time. We used GraphPad Prism (version 4.02; GraphPad Software, San Diego, CA) for statistical analyses. Where we observed significant main effects, we used the post hoc Dunn correction for multiple comparisons to assess differences between prefatigue values and those of each postfatigue test. We considered acuity recovered when error scores were no longer significantly different from their respective prefatigue values. We set the statistical significance for all comparisons at $P < .05$ a priori.

RESULTS

Subjects had a mean target velocity of 60 ± 5 mph (27.7 ± 2.2 m/s) and completed the fatigue protocol after 62 ± 28 throws. The RPE scores were 15.6 ± 0.9 at the immediate postfatigue test and 11.7 ± 2.4, 10.1 ± 2.3, and 9.0 ± 2.6 at 4-minute, 7-minute, and 10-minute recovery tests, respectively.

The Friedman test analyzing 3DVE for the arm-cocked position indicated a significant difference in acuity across time for the scapulothoracic ($\chi^2_{4,15} = 13.68$, $P < .001$), glenohumeral ($\chi^2_{4,15} = 22.30$, $P < .001$), and elbow ($\chi^2_{4,15} = 23.73$, $P < .001$) joints, as well as endpoint ($\chi^2_{4,15} = 22.32$, $P < .001$). Analysis for the ball-release position indicated a significant difference across time in the scapulothoracic ($\chi^2_{4,15} = 12.32$, $P < .001$), glenohumeral ($\chi^2_{4,15} = 11.43$, $P < .001$), elbow ($\chi^2_{4,15} = 14.34$, $P < .001$), and wrist ($\chi^2_{4,15} = 18.38$, $P < .001$) joints, as well as endpoint ($\chi^2_{4,15} = 14.58$, $P < .001$). Figures 3 and 4 illustrate results of the post hoc Dunn correction comparing 3DVE prefatigue scores with all postfatigue and recovery tests for each joint during arm-cocked and ball-release position reproduction, respectively. Figure 5 illustrates the results of the post hoc Dunn correction comparing endpoint 3DVE prefatigue scores with all postfatigue and recovery tests for reproduction of arm-cocked and ball-release positions.

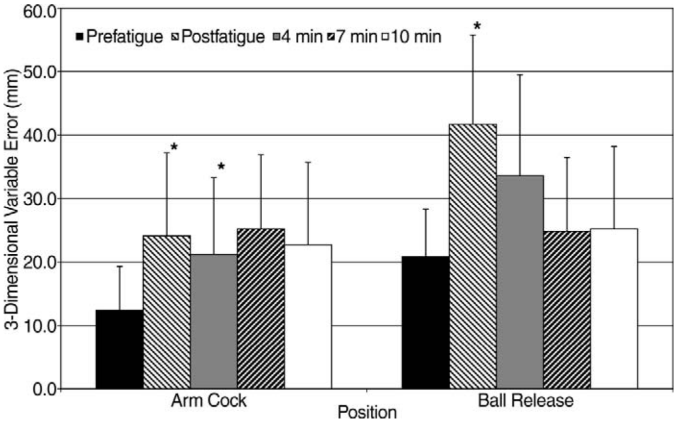

Figure 5. Analysis for recovery of upper extremity endpoint acuity (3-dimensional variable error [mean ± SD]) for reproduction of arm-cocked and ball-release positions after the throwing-fatigue protocol. Comparisons of prefatigue with postfatigue and each recovery test are presented. *Indicates significantly greater error than the respective measure's prefatigue value ($P < .001$).

DISCUSSION

Our purpose was to observe recovery of SMS acuity in overhead throwers after a functional-fatigue protocol via active multijoint position reproduction. Fatigue affected SMS acuity, causing significantly greater error in each measure of acuity except the wrist at the arm-cocked position. These results support general reports indicating that fatigue hampers upper extremity acuity[8,9,11] and reports employing a similar 3-dimensional measure and throwing-fatigue protocol.[12] Voight et al[9] theorized that fatigue affects SMS acuity by hindering normal mechanoreceptor function, which, in essence, desensitizes muscle-spindle thresholds. Proposed mechanisms for this include local metabolism interfering at the muscular level[10,11,29] and central nervous system or neuromuscular fatigue.[5,11]

We hypothesized that upper extremity acuity would recover from observed deficits within 10 minutes in a manner similar to measures of balance.[15–17] Our results indicate that during reproduction of the arm-cocked position, acuity for the elbow recovered within 4 minutes, whereas both scapulothoracic and endpoint position acuity recovered within 7 minutes. At the ball-release position, acuity of each joint and endpoint reproduction recovered within 4 minutes. Given the lack of research involving upper extremity acuity, our comparisons are limited to those observing balance as a measure of SMS function. These results support our hypothesis and the research of other authors,[15–17] indicating that SMS function recovers within 10 minutes after intense fatigue protocols. Although identifying the specific mechanism for such recovery is beyond the scope of our study, research indicates that changes in muscle electromyographic activity[30–32] and metabolic environment[33] accompanying fatigue are restored within 10 minutes. Our results indicate that 9 of the 10 measures of upper extremity SMS acuity recover in a similar timeframe.

Most acuity measures that we observed recovered in a relatively predictable manner, but acuity in the glenohumeral joint did not. During reproduction of the arm-cocked position, glenohumeral acuity failed to recover by 10 minutes. This finding may be particularly important to our understanding of the genesis of capsulolabral injuries common in overhead throwers. The arm-cocked position is implicated as a critical factor in the cause of shoulder injuries from subacromial[34,35] and posterior[34–36] impingement to labral tears.[35,37] With the glenohumeral joint in such a vulnerable position and large-magnitude forces present,[2] poor neuromuscular control may increase the risk of injury and contribute to the cycle of pathophysiology that Lephart and Henry[38] described.

Our observation that acuity in the glenohumeral joint did not recover as quickly as in other joints may be explained by the relative contribution of the associated musculature to the act of throwing and possibly the nature of the throwing-fatigue protocol itself. The primary arm accelerators during throwing are the humeral internal rotators, most notably latissimus dorsi and pectoralis major.[39] This finding is underscored by a recent observation[40] that strength deficits in glenohumeral internal rotators are greater than those of external rotators after a bout of competitive pitching. Our subjects threw at maximum velocity from a single-knee position until fatigued. We chose this position, in part, to limit the relative contribution of force from the lower extremity. The upper extremity would have to provide additional force relative to the normal demands of throwing[41] and, therefore, would fatigue more rapidly. Throwing in this manner may place greater demands on the primary accelerators of internal rotation in particular. Such a disproportionate fatigue between antagonist and agonist glenohumeral musculature may affect acuity.

Roll and Vedel[42] described such an interaction between an antagonist muscle and SMS acuity of its agonist. Activation of muscle spindles in antagonists resulted in perceived joint movement in the direction of agonist muscle contraction.[42] A similar mechanism may have influenced glenohumeral acuity in our study, but the sparse literature describing such an interaction may not apply to the active position reproduction measures that we used.

Limitations

Our results are limited to healthy, male National Collegiate Athletic Association baseball athletes with no history of upper extremity injury or surgery or central nervous system disorder and may not apply to injured players or to nonathletes. As discussed, the nature of our fatigue protocol may have affected results because the protocol placed greater relative demands on humeral internal rotators by limiting contribution of the lower extremity to force production. During our fatigue protocol, athletes threw every 5 seconds at maximum velocity, which may be more physically demanding and less mentally stressful than game situations are. Because we did not continue postfatigue measures past 10 minutes, we failed to identify when glenohumeral acuity fully recovered. We did not standardize test positions between subjects, and we recognize that they may not be precise representations of each subject's arm-cocked and ball-release positions. We chose reproduction of self-selected positions familiar to the population and believe replication of predetermined positions is too constraining. Additionally, we tested athletes in a controlled environment during the off-season; weather conditions and the demands of an in-season schedule may affect results.

Clinical Implications

Our results hold clinical implications for prescription of recovery intervals during intense overhead activity. Specifically, a minimum of 4 to 7 minutes should be allotted for recovery between fatiguing bouts of throwing to avoid accumulation of SMS deficits. Such deficits in SMS function have been associated with upper extremity disorders.[7,43–45] We observed SMS deficits at multiple joints, indicating clinicians may consider including multijoint upper extremity rehabilitation and prevention activities for throwers. Given the failure of the glenohumeral joint to recover as quickly as other upper extremity joints, it may be appropriate to emphasize SMS acuity and endurance in abduction and external rotation. Increasing upper extremity endurance may help stave off fatigue and thereby avoid the accompanying deleterious effects during repetitive activity.

CONCLUSIONS

To our knowledge, this is the first report describing short-term recovery of SMS acuity in the upper extremity after functional fatigue. Our results indicate that fatigue diminishes acuity at multiple upper extremity joints and over the extremity as a whole. Active SMS acuity recovered in 9 of the 10 measures within 4 to 7 minutes, which mirrors recovery of other physiologic byproducts of fatigue. The glenohumeral joint failed to recover after 10 minutes, perhaps reflecting the greater relative demands placed on arm accelerators during our throwing-fatigue protocol.

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