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The Effects of Muscular Fatigue on Shoulder Proprioception

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Abstract:

Objective: To assess the influence of muscular fatigue on active and passive shoulder proprioception within the midrange of rotation.

Design: A randomized controlled, before-and-after design.

Setting: Neuromuscular research laboratory.

Participants: Twenty recreationally active men (mean age, 23.81 ± 2.77 years) were randomly assigned to either a control or a fatigue group. Exclusion criteria were any history of upper extremity injury or pathology, cardiovascular disease, or disease affecting the sensory system.

Intervention: Shoulder proprioception was assessed by active reproduction of passive positioning (ARPP), active reproduction of active positioning (ARAP), reproduction of passive positioning (RPP), and threshold to detect passive motion (TTDPM). For each test direction, the experimental group performed two bouts of maximal reciprocal concentric isokinetic internal and external contractions at 180°/s until peak torque decreased to 50% of the established maximum voluntary contraction. After two bouts of the fatigue protocol, subjects were randomly assessed for proprioception into internal or external rotation.

Main Outcome Measures: The absolute angular error for active and passive proprioception was measured on the Biodex System II Isokinetic Dynamometer (Biodex Medical Inc., Shirley, NY, U.S.A.) and a proprioception testing device, respectively.

Main Results: A two-factor repeated measures analysis of variance revealed no significant interactions between the experimental and control groups for ARPP, ARAP, RPP, or TTDPM.

Conclusions: Shoulder proprioception was not affected by the short-duration, high-intensity protocol used in this study. This may be due to the lack of an extended recovery period observed with this type of fatigue regimen.

Key Words: Joint position sense—Kinesthesia—Neuromuscular control—Muscular fatigue.

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Proprioception has been referred to as a neuromuscular mechanism encompassing the sensations of joint position and movement (15,17,19). This specialized sensation is a highly complex interdependent system of afferent mechanoreceptors responsible for adapting to unexpected perturbations, facilitating movement through segmental interactions and providing synergistic muscular contractions to maintain joint stability (5).

It is well known that the shoulder is an inherently unstable joint that relies on static and dynamic structures for stability. However, considerable controversy over the role mechanoreceptors located within these structures play in maintaining joint stability persists. Traditionally, investigators have viewed joint receptors as the predominant neural structure contributing to joint position and movement sense (5,7,8,21). Recent studies, however, indicate that articular structures are lax within the midranges of shoulder rotation (8,20), thereby minimizing mechanoreceptor responses to joint perturbations within the intermediate ranges of motion (4,5,13,27,29). Clark et al. (6) reported that anesthesia to the interosseous muscle in the metacarpophalangeal joint of the finger resulted in diminished position sense. Gandevia and McCloskey (10) demonstrated that surgical removal of the musculature around the distal interphalangeal joint in the finger produced a deficit in movement sense. These findings suggest that there may be some activation overlap between articular and musculature mechanoreceptors (13). As a result, it is currently believed that the predominant mechanoreceptor contributing to proprioceptive appreciation throughout the midrange of rotation is that of the muscle mechanoreceptors (4,8,14,18,20,25,29).

Muscular fatigue has been defined as the inability to maintain force output, resulting in a decrease in performance (9,12). It has been suggested that muscular fatigue produces neuromuscular deficiencies within the muscle, thus predisposing a joint to injury and the eventual decrease in athletic performance (12,24,28). Recent clinical investigations have demonstrated that fatigue negatively effects joint proprioception through deficiencies in either

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muscle mechanoreceptor activation or decreases in muscle function (24,28).

It is believed that passive proprioception assessment predominantly measures the stimulation of joint mechanoreceptors during movement sense and joint position sense by minimizing muscle mechanoreceptor involvement (1,5,15,17). The active components of muscle, however, may provide a more functional measurement of proprioception. Thus, a comprehensive assessment of shoulder proprioception in a position that maximizes musculotendinous mechanoreceptor involvement may provide a more clear understanding of the role of muscular fatigue on joint position awareness. The purpose of this investigation was to examine the influence of an isokinetic fatigue protocol on active and passive shoulder proprioception within the midrange of rotation.

METHODS

Subjects

Twenty male volunteers (average age, 23.81 ± 2.77 years; height, 177.09 ± 6.25 cm; weight, 82.45 ± 13.69 kg) from the general student population at the University of Pittsburgh were included in this investigation. All subjects were recreationally active for a minimum of three times per week. Exclusion criteria included history of upper extremity orthopedic injury or pathology, cardiovascular or coronary disease, or disease affecting the sensory system. All subjects provided written informed consent approved by the Biomedical Institutional Review Board of the University of Pittsburgh.

Experimental design

A randomized, controlled, before-and-after design was used in this investigation. The dependent variables for this study included the absolute angular error (AAE) as measured during four testing protocols: active reproduction of active positioning (ARAP), active reproduction of passive positioning (ARPP), reproduction of passive positioning (RPP), and threshold to detect passive motion (TTDPM). Measurements of the dependent variables were counterbalanced between three test sessions. Counterbalancing the test sessions was used to eliminate any ordering effect. This was accomplished by organizing the test sessions into three possible combinations: ARPP, ARAP, RPP and TTDPM; ARAP, RPP and TTDPM, ARPP; and TTDPM and RPP, ARPP, ARAP. RPP and TTDPM were assessed in one session to decrease the variability in patient setup on the proprioception testing device. Evaluations of RPP and TTDPM were further counterbalanced among the subjects within a single session.

An equal number of subjects were randomly assigned to either an experimental (fatigue) or a control group. All subjects had a minimum of 7 days between each test session to allow the fatigue group to recover from muscle soreness that may have resulted from the treatment regimen. In addition, testing was conducted at the same time of day under similar environmental conditions to reduce the effect of diurnal variations.

The control group underwent the same testing procedures as the experimental group but did not perform the fatigue protocol. Five-minute periods were implemented between the control group's pretest and posttest evaluations. These time periods approximated the estimated length of the treatment protocol for the experimental group.

Testing of the fatigue group proceeded with a counterbalanced three trial pretest in either ARPP, ARAP, or RPP and TTDPM for internal and external rotation. This pretest was followed by the first set of fatigue bouts. A three trial posttest in either internal or external rotation was administered immediately after the cessation of fatiguing contractions. The fatigue protocol was readministered with a final posttest completed in the direction not previously tested. Test directions were randomized between fatigue sets to nullify any differences in fatigue levels resulting from multiple treatments.

Materials

All tests were conducted using the Biodex System II Isokinetic Dynamometer (Biodex Medical Systems Inc., Shirley, NY, U.S.A.) and the proprioception testing device (PTD). Before testing, shoulder goniometric measurements were obtained, using a standard handheld goniometer to determine each subject's physiologic midrange of motion within internal and external rotation. The midrange angle was calculated by passively rotating the shoulder to its end range of motion and dividing this number by 2.

Subjects had their upper torso exposed during all testing sessions to prevent clothing from giving proprioceptive cues through skin mechanoreceptor neural stimulation (24). Blindfolding denied visual cues to subjects during all proprioception tests. Headphones playing static noise were also included during TTDPM testing to prevent auditory cues during testing. Subjects were positioned supine on the horizontally reclined Biodex System II System Accessory Chair. Trunk and pelvic stabilization restraints secured the participant to the chair in order to decrease extraneous movement from the scapula, trunk, and legs during the treatment protocol. A forearm restraint was attached to the Biodex System II Shoulder Adapter which decreased fortuitous movement at the elbow during the fatigue protocol. These restraining devices were then removed during proprioception examinations. Hand placement was on the hand grip connected to the lever arm of the Biodex System II Shoulder Adapter.

Proprioception testing

Four quantifiable methods of testing proprioception were used in this investigation. All active and passive proprioception examinations except for TTDPM began at a reference angle of 90° shoulder abduction, 90° elbow flexion, and neutral shoulder rotation. ARPP and ARAP were evaluated on the Biodex System II Isokinetic Dynamometer. During ARPP, subjects were instructed to relax as the investigator slowly rotated their shoulder to the test angle. Subjects were given 10 seconds to concentrate on the test angle before their shoulder was passively returned to the reference angle. At this point, the

participant was instructed to actively attempt to reproduce the test angle. ARAP was evaluated similarly, but subjects actively oriented themselves to the test angle. This was accomplished by the examiners' placing a range of motion block on the dynamometer in order to cue subjects upon reaching the test angle. Reproduction attempts were discontinued by the subjects' pressing a handheld stop button at the perception of the test angle.

Reproduction of passive positioning and threshold to detect passive motion were tested on a PTD (1,5,17,26) that measured the angular displacement using a rotational transducer interlaced with a digital microprocessor (1,5,17,26). The hand and forearm were placed in a pneumatic compression sleeve attached to the drive shaft of the PTD for evaluation of RPP and TTDPM. Reproduction of passive positioning was examined with each subject in a relaxed position as the PTD rotated his shoulder to the presented angle. Following a 10-second interval, the PTD was returned to the reference position. Subjects received no information regarding the speed of the PTD's rotation. Variable speeds were used during movement to and from the presented angle in order to negate time cues between trials (5,17). Reproduction of the presented angle began as the examiner initiated rotation of the PTD at 2°/s. Subjects were instructed to press the stop button connected to the PTD at the perception of the angle.

Threshold to detect passive motion was measured at each subject's anatomic midrange of motion for both external and internal rotation. Each test direction received three trials of randomized movements into internal and external rotation. Movement of the PTD (0.5°/s) began 1 to 10 seconds after notifying the subject (tap on the upper leg) that the test was about to begin. Previous investigations have suggested that movements of less than 1°/s maximally stimulate joint receptors with minimal involvement from the muscular mechanoreceptors (5,11,15,17). PTD rotation was disengaged by the subjects' pressing the stop button upon perceiving movement in the shoulder.

Fatigue protocol

A modified version of the fatigue protocol used by Schwendner et al. (22) was used in this study. The start position for the fatigue protocol was at 90° of shoulder abduction, 90° of elbow flexion, and 90° of external rotation. Subjects warmed up with 15 submaximal concentric contractions on the isokinetic dynamometer followed by five maximal reciprocal concentric contractions for shoulder external and internal rotation at 180°/s. The highest peak torque of the five repetitions for external rotation determined each participant's maximum voluntary contraction (MVC). Immediately after the establishment of the MVC, each subject performed a two-set fatigue protocol for each testing session with two fatigue bouts in each set. Fatigue bouts consisted of continuous maximal reciprocal concentric contractions until external rotation peak torque decreased below 50% of the established MVC. A 30-second rest period followed each fatigue bout. The initial three external rotation contractions for the second and fourth bouts reestablished the MVC for their respective bouts. Resetting the MVC was used to nullify fatigue recovery during the 30-second rest period (22).

Schwendner et al. (22) has suggested that a 50% decrease in force output is a significant indication of fatigue level. It was reported that subjects with the greatest decrease in force output required the longest recovery time ($r = 0.69$). A fatigue window lasting a minimum of 2 minutes was also reported following this study's isokinetic protocol. The present investigation used this fatigue protocol in an attempt to quantify fatigue levels for each subject (22).

Data analysis

A two-factor analysis of variances (group by test) with repeated measures was performed on the AAE for each measure of proprioception at a preset alpha level of 0.05. A lower AAE value indicates a more accurate reproduction of position and movement sense. The absolute error in reproduction was selected as the variable for this study because it has not yet been established if either underestimating or overestimating a reproduced angle are correlated with specific proprioceptive deficits. The data was analyzed on the Statistical Package for the Social Sciences (SPSS) software program, version 6.1 (SPSS, Inc., Chicago, IL, U.S.A.).

RESULTS

Mean and standard deviation AAE values for ARPP, ARAP, RPP, and TTDPM for the control and fatigue group are presented in Table 1. Statistical analysis revealed that two bouts of reciprocal concentric internal and external contractions had no overall main effect on active or passive shoulder proprioception. These findings were evident as no significant group by test interactions were found for ARAP in either external ($F_{1,19} = 1.57$; $p = 0.23$) or internal ($F_{1,19} = 0.45$; $p = 0.51$) rotation.

The results of this investigation also revealed that muscular fatigue had no significant effect on ARPP. These findings were demonstrated as no significant group by test interactions were found for either external ($F_{1,19} = 0.97$; $p = 0.34$) or internal ($F_{1,19} = 0.01$; $p = 0.92$) rotation. A group main effect was found as the mean pretest and posttest scores for the control group were significantly higher than the combined pretest and posttest scores for the fatigue group ($F_{1,19} = 5.66$; $p = 0.03$).

The findings in this study also demonstrated that the ability to reproduce a passively positioned angle (RPP) was not significantly affected by the two-bout fatigue protocol to 50% of the established MVC. The two-factor repeated measures analysis of variance found no significant group by test interactions for either external ($F_{1,19} = 1.03$; $p = 0.32$) or internal ($F_{1,19} = 0.13$; $p = 0.73$) rotation.

The results of the present investigation also revealed that muscular fatigue had no significant effect on TTDPM for both external ($F_{1,19} = 0.18$; $p = 0.68$) and

TABLE 1. *Proprioception values (means ± SD) for the control and fatigue groups*

	Before the test		After the test	
	Fatigue	Control	Fatigue	Control
ARAP				
Internal rotation	3.67 ± 2.24	2.81 ± 1.70	3.23 ± 1.90	3.17 ± 1.40
External rotation	5.50 ± 2.86	4.36 ± 2.89	3.09 ± 3.11	4.33 ± 2.72
ARPP				
Internal rotation	4.43 ± 2.89	3.45 ± 2.02	4.63 ± 2.30	3.82 ± 2.13
External rotation	4.77 ± 2.79	8.40 ± 3.69	4.66 ± 2.55	6.49 ± 4.05
RPP				
Internal rotation	4.59 ± 3.28	2.80 ± 3.10	3.66 ± 2.78	2.47 ± 2.25
External rotation	6.45 ± 7.13	10.49 ± 6.14	7.30 ± 4.57	8.45 ± 5.15
TTDPM				
Internal rotation	1.86 ± 0.69	2.54 ± 2.23	2.18 ± 0.90	2.92 ± 2.71
External rotation	1.60 ± 0.49	3.12 ± 2.89	3.06 ± 2.57	4.13 ± 5.01

ARAP, active reproduction of active positioning; ARPP, active reproduction of passive positioning; RPP, reproduction of passive positioning; TTDPM, threshold to detect passive motion.

internal ($F_{1,19}$ = 0.02; p = 0.90) rotation as demonstrated by no significant group by test interactions.

DISCUSSION

The major findings of the present study demonstrated that a two-bout fatigue regimen to 50% decrease from the MVC did not impair active and passive shoulder proprioception for either internal or external rotation.

Active reproduction of active positioning

Marks and Quinney (19) examined knee proprioception within the midrange of rotation in healthy and osteoarthritic patients. These authors reported significantly greater errors in joint position sense in the osteoarthritic group than in the healthy subjects. It was suggested that these deficits within the intermediate range were possibly due to degenerative changes to the muscle mechanoreceptors (19). Based on this research, the present study presumed that muscular fatigue would affect muscle mechanoreceptors during ARAP testing. The fatigue protocol revealed, however, a small but nonsignificant change in AAE. This appears contrary to the findings of Lattanzio et al. (16), who found a significant increase in AAE of the knee after three different fatigue protocols. The exercise protocols used by Lattanzio et al. (16) involved prolonged cycle ergometry, which may have influenced the involvement of different fatigue mechanisms. In addition, proprioception measures in the present study were performed in the open kinetic chain position, whereas Lattanzio et al. (16) incorporated a closed kinetic chain position. The differences in fatigue protocols and proprioception testing position (open vs closed kinetic chain) may account for these contrary findings.

Threshold to detect passive position

The present findings appear to concur with those of Skinner et al. (24), who reported a nonsignificant improvement in the detection of passive movement within the midrange of knee rotation after interval running. Although it may appear that the AAE for TTDPM increased, statistical analysis revealed that this change was not significant for both external and internal rotation subsequent to the isokinetic fatigue protocol. Skinner et al. (24) suggested that a "change in the neural mechanism" occurred in order to maintain movement sense after fatigue. These authors proposed that a decrease in muscle mechanoreceptor activity due to fatigue resulted in an increase in capsular stress, thus enhancing articular receptor activity.

The slow rate of rotation (0.5°/s) for proprioception testing, combined with muscular fatigue, in the present investigation may have inhibited muscular receptor involvement during TTDPM testing (11). It may be speculated that the nonsignificant changes in AAE for TTDPM may be due to the auxiliary roles of the articular mechanoreceptors to maintain movement sense in the absence of muscular mechanoreceptor involvement (8).

Reproduction of passive positioning

The results of the present investigation did not demonstrate a detrimental effect of fatigue on the ability to passively reproduce a passively positioned angle. These findings appear to refute those of Voight et al (28). These investigators reported an AAE of 30.40° for RPP in the dominant shoulder (at 75° of external rotation) after one bout of fatiguing contractions. Subsequent to a two-bout fatigue regimen, the current investigation demonstrated an AAE for RPP of 0.32° into internal and 1.46° into external rotation after the fatiguing contractions.

Voight et al. (28) concluded that the inability to reproduce a passively positioned angle "at the end range of motion" was due to a desensitization of the muscle mechanoreceptors and dysfunction of the muscular components. This is contrary to current research proposing that the predominant mechanoreceptor contributing to joint position sense at the terminal ranges of motion is the articular receptor (10). Previously, it has also been demonstrated that acute cyclic exercise increases joint laxity (25,29). Weisman (29) suggested that this increase in joint compliance may hinder the ligamentomuscular reflex through an increase in the toe region in the load-deformation curve. As a result, the wavy collagenous fibers in the articular structures may require greater de-

formation to orient themselves to the stress incurred during cyclic movement. This increase in deformation may delay the activation of the articular mechanoreceptors at the end range of motion. Thus, the findings of Voight et al. (28) may be indicative of a fatigue effect on articular mechanoreceptors at the terminal range of motion rather than on the muscle mechanoreceptors.

Active reproduction of passive positioning

The current study revealed a nonsignificant change within the midrange of internal and external rotation for ARPP after the induction of muscular fatigue. These findings do not appear to agree with those of Voight et al. (28), who reported a significant decrease in joint position sense at 75° of external rotation in the dominant shoulder after a one-bout fatigue protocol. As mentioned previously, it has been suggested that these results demonstrate changes to both the articular and the muscular mechanoreceptors, rather than to muscular receptors alone, as suggested by Voight et al. (28).

Although Skinner et al. (24) reported examining passive joint position, an active component actually existed in their evaluation of RPP. Subjects were asked to actively reproduce a passively positioned angle, thereby evaluating ARPP. This study appears to be comparable with the current investigation because both examined proprioception within the midrange of rotation ensuing muscular fatigue. Skinner et al. (24) found a significant decrease in the ability to actively reproduce a passively positioned angle after interval running. Alternatively, the two-bout isokinetic fatigue protocol used in the current study resulted in a nonsignificant change in ARPP for both internal and external rotation. The variability of scores between the current study and those of Skinner et al. (24) may be a result of different recovery rates from the types of fatigue protocols used in these investigations.

Previous research has demonstrated that recovery from muscular fatigue depends on the intensity and duration of the exercise used (2,14). Muscular force impairments have been shown to remain below prefatigue levels for as long as 24 hours after long-duration, low-intensity exercise (low-frequency fatigue) (2,14). Baker et al. (2) reported that 20 minutes of intermittent isometric contraction in the tibialis anterior prevented peak voluntary force from reaching baseline values within a 15-minute recovery period. Consequently, the interval running combined with the long-duration protocol suggests that Skinner et al. (24) used a low-frequency fatigue regimen to delay recovery from muscular fatigue, thereby increasing the possibility of assessing proprioception in a fatigued state.

Contrary to the prolonged recovery rate observed in low-frequency fatigue, exercise protocols comprising high-intensity, short-duration muscular contractions (high-frequency fatigue) have been shown to demonstrate rapid recovery of muscular force (2,3,23). Sinacore et al. (23) observed a 2- to 4-minute recovery of voluntary force after isokinetic knee extension contractions at 180°/s. Similarly, Beelen et al. (3) found that peak voluntary force was reported to recover within 3 minutes after two 45-second bouts on an isokinetic cycle ergometer at a pedal velocity of 60 rpm.

The current investigation proposes that rapid recovery from muscular fatigue occurred during the proprioception evaluations. The time to 50% of the established MVC was ~1 minute for all bouts. The MVC was reduced between the first and second bouts (76% of initial MVC) and the third and fourth bouts (78% of initial MVC), suggesting that the two-bout fatigue protocol induced muscular fatigue. A posttest was performed after the cessation of the second bout. Approximately 2 or 3 minutes elapsed between the cessation of the second bout and the reestablishment of the MVC for the third bout. Table 2 illustrates that the MVCs for the third bout recovered to 93% of the value of the MVCs of the first bout. This provides evidence that the recovery rates observed in the current study appear to coincide with those of high-frequency fatigue. Thus, the rapid recovery of the MVCs also suggests that shoulder proprioception was not examined in a prolonged fatigued state.

CONCLUSIONS

The current investigation demonstrated that the short-duration, high-intensity muscular fatigue protocol used did not impair shoulder proprioception within the midranges of external and internal rotation. It is suggested that this type of regimen did not provide an extensive recovery period to allow for an accurate assessment of the effect of fatigue on shoulder proprioception. It is suggested that future research investigate those exercise protocols that will prolong recovery from muscular fatigue in the shoulder. The application of these low-frequency exercise protocols may provide a clearer indication of the detrimental effects of muscular fatigue on the ability to consciously perceive joint position and movement.

TABLE 2. *MVC and time to 50% of the established MVC values (means ± SD) for the fatigue group*

	First bout		Second bout		Third bout		Fourth bout	
Session	MVC (N · m)	Time (s)	MVC (N · m)	Time (s)	MVC (N · m)	Time (s)	MVC (N · m)	Time (s)
1	33.69 ± 2.20	61.00 ± 4.36	23.30 ± 1.66	59.80 ± 5.20	31.86 ± 1.70	48.70 ± 3.72	24.45 ± 1.20	58.30 ± 5.89
2	34.99 ± 9.57	54.80 ± 10.37	26.11 ± 7.09	50.50 ± 15.59	31.18 ± 8.87	53.50 ± 17.14	24.60 ± 6.94	43.90 ± 17.10
3	30.67 ± 4.60	61.10 ± 23.39	26.00 ± 4.42	51.15 ± 18.11	29.61 ± 5.37	56.00 ± 17.13	23.41 ± 3.71	52.50 ± 14.33

MVC, maximum voluntary contraction.

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REFERENCES

1. Allegrucci M, Whitney SL, Lephart SM, Irrgang JJ, Fu FH. Shoulder kinesthesia in healthy unilateral athletes participating in upper extremity sport. *J Orthop Sport Phys Ther* 1995;21:220–6.
2. Baker AJ, Kostov KG, Miller RG, Wiener MW. Slow force recovery after long duration exercise: metabolic and activation factors in muscle fatigue. *J Appl Physiol* 1993;74:2294–300.
3. Beelen A, Sargeant AJ, Jones DA, deRuiter CJ. Fatigue and recovery of voluntary and electrically elicited dynamic force in humans. *J Physiol* 1995;484:227–35.
4. Bigliani LU, Pollock RG, Soslowsky LJ, Flatow EL, Pawluk RJ, Mow VC. Tensile properties of the inferior glenohumeral ligament. *J Orthop Res* 1992;10:187–97.
5. Borsa PA, Lephart SM, Kocher MS, Lephart SP. Functional assessment and rehabilitation of shoulder proprioception for glenohumeral instability. *J Sport Rehab* 1994;3:84–104.
6. Clark FJ, Burgess RC, Chapin JW. Proprioception with the proximal interphalangeal joint of the index finger: evidence for a movement sense without a static-position sense. *Brain* 1986;109:1195–208.
7. Clark FJ, Horsh KW, Bach SM, Larson GF. Contributions of cutaneous and joint receptors to static knee position sense in man. *J Neurophysiol* 1979;42:877–88.
8. Ferrell WR, Gandevia SC, McCloskey DI. The role of joint receptors in human kinesthesia when intramuscular receptors cannot contribute. *J Physiol* 1987;386:63–71.
9. Fitts RH. Cellular mechanisms of muscle fatigue. *Physiol Rev* 1994;74:49–74.
10. Gandevia SC, McCloskey DI. Joint sense, muscle sense, and their combination as position sense, measured at the distal interphalangeal joint of the middle finger. *J Physiol* 1976;260:387–407.
11. Goodwin GM, McCloskey DI, Mathews PBC. The persistence of appreciable kinesthesia after paralysing joint afferents but preserving muscle afferents. *Brain Research* 1972;37:326–9.
12. Green HJ. Neuromuscular aspects of fatigue: *Can J Sport Sci* 1987; 12(suppl 1):7s–19s.
13. Grigg P. Peripheral neural mechanisms in proprioception: *J Sport Rehab* 1994;3:2–17.
14. Lannergren J, Westerblad H, Bruton JD. Slow recovery of force in single skeletal muscle fibers. *Acta Physiol Scand* 1996;156:193–202.
15. Lephart SM, Fu FH, Borsa PA. Proprioception in sports medicine. In: *Adv Operative Orthop*, vol 2. St Louis: Mosby-Year Book, 1994:77–93.
16. Lattanzio PJ, Petrella RJ, Sproule JR, Fowler PJ. Effects of fatigue on knee proprioception. *Clin J Sport Med* 1997;7:22–7.
17. Lephart SM, Pincivero DM, Giraldo JL, Fu FH. The role of proprioception in the management and rehabilitation of athletic injuries. *Am J Sports Med* 1997;25:130–7.
18. Mountcastle VS. *Medical physiology*, ed 14. St Louis: Mosby, 1980.
19. Marks R, Quinney AH. Position sense perception at the knee in healthy persons and persons with chronic degenerative arthritis. *Clin Kinesiol* 1996;50:76–82.
20. Obrien SJ, Neves MC, Arnoczy SP, Rozbruck RS, Picarlo EF, Warren RF, Schwartz R, Wickiewicz TL. The anatomy and histology of the inferior glenohumeral ligament complex of the shoulder. *Am J Sports Med* 1990;8:449–56.
21. Rowinski, MJ. Afferent neurobiology of the joint. In: Gould JA, ed. *Orthopedic and sports physical therapy*. St. Louis: Mosby, 1990:50–64.
22. Schwendner KL, Mikesky JK, Wigglesworth JK, Burr DB. Recovery of dynamic muscle function following isokinetic fatigue testing. *Int J Sports Med* 1995;16:185–9.
23. Sinacore DR, Bander BL, Delitto A. Recovery from a one minute bout of fatiguing exercise: characteristics, reliability and responsiveness. *Phys Ther* 1994;74:234–54.
24. Skinner HB, Wyatt MP, Hodgdon JA, Conrad DW, Barrack RL. Effect of fatigue on joint sense of the knee. *J Orthop Res* 1986;4: 112–8.
25. Skinner HB, Wyatt MP, Stone ML, Hodgdon JA, Barrack RL. Exercise related knee joint laxity. *Am J Sports Med* 1986;14:30–4.
26. Swanik CB, Henry TJ, Lephart SM. Chronic brachial plexopathies and upper extremity proprioception and strength. *J Athl Train* 1996;31:119–29.
27. Tyldesley B, Gieve JI. *Muscles, nerves, and movement: kinesiology in daily living*. Boston: Blackwell Scientific Publications, 1989.
28. Voight ML, Harden JA, Blackburn TA, Tippet S, Canner GC. The effects of muscle fatigue on and the relationship of arm dominance to shoulder proprioception. *J Orthop Sport Phys Ther* 1996;23: 348–52.
29. Weisman G, Pope MH, Johnson RJ. Cyclic loading in knee ligament injuries. *Am J Sports Med* 1980;8:24–30.