The Influence of External Loads on Movement Precision During Active Shoulder Internal Rotation Movements as Measured by 3 Indices of Accuracy

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**Context:** Using constant, variable, and absolute error to measure movement accuracy might provide a more complete description of joint position sense than any of these values alone.

**Objective:** To determine the effect of loaded movements and type of feedback on shoulder joint position sense and movement velocity.

**Design:** Applied study with repeated measures comparing type of feedback and the presence of a load.

**Setting:** Laboratory.

**Patients or Other Participants:** Twenty healthy subjects (age = 27.2 ± 3.3 years, height = 173.2 ± 18.1 cm, mass = 70.8 ± 14.5 kg) were seated with their arms in a custom shoulder wheel.

**Intervention(s):** Subjects internally rotated 27° in the plane of the scapula, with either visual feedback provided by a video monitor or proprioceptive feedback provided by prior passive positioning, to a target at 48° of external rotation. Subjects performed the internal rotation movements with video feedback and proprioceptive feedback and with and without load (5% of body weight).

**Main Outcome Measure(s):** High-speed motion analysis recorded peak rotational velocity and accuracy. Constant, variable, and absolute error for joint position sense was calculated from the final position.

**Results:** Unloaded movements demonstrated significantly greater variable error than for loaded movements (2.0 ± 0.7° and 1.5 ± 0.4°, respectively) (P < .05), but there were no differences in constant or absolute error. Peak velocity was greater for movements with proprioceptive feedback (45.6 ± 2.9°/s) than visual feedback (39.1 ± 2.1°/s) and for unloaded (47.8 ± 3.6°/s) than loaded (36.9 ± 1.0°/s) movements (P < .05).

**Conclusions:** Shoulder joint position sense demonstrated greater variable error unloaded versus loaded movements. Both visual feedback and additional loads decreased peak rotational velocity.

**Key Words:** proprioception, kinesthesia, shoulder function

Investigators researching shoulder proprioception typically evaluate either joint position sense (JPS), the ability to replicate a fixed target, or kinesthesia, the ability to detect onset of passive motion. Evaluating JPS involves either active or passive reproduction of a previously presented position or target. Passive movement toward the target is measured to diminish the influence of the gamma motor system on muscle spindles, whereas active movements are more representative of human movements.

Active and passive tests of JPS have not shown significant differences. Mechanoreceptors from cutaneous, articular, and musculotendinous regions, in addition to visual feedback (VF), can influence movement accuracy because the central nervous system (CNS) integrates all of this feedback. When vision is obscured, the CNS can maintain movement accuracy to some degree through proprioceptive feedback (PF) alone. Although movements without vision are clearly less accurate, how PF influences performance is unknown. However, the contribution of PF to maintaining function is believed to be fairly substantial. It is also difficult to determine the influence of each of these receptors (musculotendinous, articular, and cutaneous) on proprioceptive ability.

Three types of muscle receptors contribute to joint proprioception: static and dynamic muscle spindles and Golgi tendon organs (GTOs), in which muscle spindles play the dominant role. Joint receptors play a greater role near the end range of a joint, whereas cutaneous receptors contribute more position sense in the hand than in other joints. Muscle spin-
dles lie in parallel with extrafusal muscle fibers and provide proprioceptive feedback regarding muscle length and change in length (velocity). Spindles are also involved with the monosynaptic stretch reflex. However, the GTO lies in series with extrafusal muscle fibers near the musculotendinous junction and provides feedback of force within the muscle tendon complex. The GTO is more sensitive to forces generated with active movement than with passive stretching of the muscle-tendon complex. The GTO responds to active tension within a muscle-tendon complex and may influence JPS during loaded movements.

Although muscle spindle afferents (Ia and II) provide a direct connection to the alpha motor neuron in the spinal cord, only indirect connections exist between GTO afferents (Ib) and the alpha motor neuron. Instead, a wide array of connections serve the muscle of afferent origin via interneurons in the spinal cord to the alpha motor neuron but also neurons affecting synergists and antagonist muscles and higher centers of the CNS. These interneurons make it difficult to determine the exact role of the GTO in movement control. It was originally believed that the GTO provided only autogenic inhibition or self-inhibition during maximal muscle activation to prevent muscular injury. However, autogenic inhibition from the GTO is relatively weak, compared with feedback from spindle afferents and GTOs, and it is also more responsive at submaximal levels of muscle activation. Interneurons that receive feedback from the GTO also receive afferent feedback from joint and cutaneous receptors, which appear to enhance the inhibition from the GTO. This type of peripheral feedback is thought to prevent the use of excessive force to overcome potentially immovable objects that can be encountered during voluntary movements. The role of the GTO in JPS and kinesthesia is unclear and in need of further study.

Shoulder JPS is reported as performance, or movement accuracy, in terms of “average mean difference error” or constant error (CE) of angular position of a rotated humerus with respect to a previously described fixed angular position. Other measures of accuracy or consistency include variable error (VE) and absolute error (AE). Calculations of these measures are provided in the Methods section. Absolute error might be a more sensitive method of measuring accuracy than CE; however, CE gives an indication of the direction error, whereas VE provides information regarding consistency of a performance.

Consistently overshooting a target generates a small VE and larger CE and AE values. Conversely, a high degree of inconsistency (VE) can also be generated with small CE scores: inconsistent accuracy. Using all 3 measures of performance could provide a more complete description of performance based on overall accuracy (AE), a measure of the direction of the error (CE), and the variability of the performance (VE).

Our main purpose was to determine the effect of external loads on movement accuracy and movement velocity with VF and PF or proprioceptive feedback alone. A secondary purpose of this study was to determine if differences in performance between loaded and unloaded movements can be determined with measures such as CE, VE, and AE.

METHODS

Subjects

Twenty subjects, with equal numbers of males and females (age = 27.2 ± 3.3 years, height = 173.2 ± 18.1 cm, mass = 70.8 ± 14.5 kg) were recruited from the general student population. Subjects were screened by a certified athletic trainer with a brief medical history and assessment of glenohumeral range of motion (internal and external rotation), upper extremity muscle strength, and upper quarter sensation. We used these tests to exclude individuals with a history of shoulder injury, such as glenohumeral dislocation or chronic subluxation, or any injury that could result in neurovascular compromise to the dominant upper extremity. All subjects provided informed written consent. The institutional review board reviewed and approved the protocol for this study.

The subjects’ dominant upper extremity, defined as the extremity with which they preferred to throw, was tested. All subjects were right-hand dominant. Subjects’ internal and external ranges of motion for the right glenohumeral joint were 51.7 ± 15.2° and 87.5 ± 13.7°, respectively.

Instrumentation

Data Acquisition: Video Capture System. Kinematic data were recorded by 3 high-speed Falcon Cameras (Motion Analysis Corp, Santa Rosa, CA) positioned around the shoulder wheel, approximately 5 m away and elevated approximately 4 m above the floor. Data were collected at a sampling rate of 240 Hz. Spatial, 3-dimensional coordinate data for the 3 retrolrefective markers were determined using the direct linear transformation as modified with Motion Analysis software. Coordinate data were smoothed with a 4th-order, zero-lag, low-pass Butterworth filter with a cutoff frequency of 6 Hz. We used standard trigonometry to calculate the angle formed by the stationary arm and the movable arm of the shoulder wheel (EVa software, Motion Analysis Corp). Angular displacement of the movable arm of the shoulder wheel relative to the stationary arm enabled approximation of the instantaneous angular position for shoulder wheel internal rotation. The instantaneous angular velocity for shoulder internal rotation movement was calculated using central differences.

Thumb Switch. The subjects activated a thumb switch, connected to a 9-V battery, to indicate when they thought they had reached the target position. The analog signal from the thumb switch (collected at 960 Hz) was synchronized with the motion capture system. The final location of the movable arm of the shoulder wheel, representing the subject’s ability to replicate the target, was defined as the angular position of the wheel when instantaneous angular velocity of the wheel was nearest zero before activating the thumb switch (Figure 1).
Subjects start from the position of 75° (starting position of external rotation) to 0°, or neutral, in order to prevent injury. The buttress that limited external rotation also provided a consistent starting position for all subjects. A movable third buttress was used to consistently place each subject’s shoulder at the target position of 48° of external rotation, or 27° from the starting position. The buttress was moved out of the way as required during data collection trials. The angular displacement in this study was similar to that in previous shoulder proprioception studies.1,2,28 Moreover, this position is an attempt to replicate arm position during throwing, which has been used in previous studies of shoulder proprioception and can have an effect on accuracy of performance (ie, throwing).25,30

Constant error, or CE, is calculated as follows:

$$CE = \frac{\sum (x_i - T)}{n}$$

where \(x_i\) is the individual trial, \(T\) is the target, and \(n\) is the number of trials. Other measures of movement accuracy include VE and AE and are calculated as follows:

$$VE = \sqrt{\frac{\sum (x_i - \bar{X})^2}{n}}$$
$$AE = \frac{\sum |x_i - T|}{n}$$

where \(x_i\) is the individual trial, \(\bar{X}\) is the mean of the trials collected, \(T\) is the target position, and \(n\) is the number of trials collected.

**Subject Position.** Subjects sat upright with the arm and shoulder in the plane of the scapula and the shoulder abducted and horizontally adducted to 90° and 30°, respectively.31 The elbow was flexed to 90° with the forearm in a neutral position. The forearm was inserted into a custom-made shoulder wheel and stabilized by a compressive sleeve around the forearm (see Figure 2A). The glenohumeral joint axis of rotation was visually aligned with the axis of rotation of the shoulder wheel. Subjects wore goggles with a shield to block peripheral vision and to prevent direct visualization of the arm, forearm, hand, and shoulder wheel during all trials.

**Proprioceptive Feedback**

Subjects were passively moved from the starting position to the target position, approximating the movable buttress that was put into place, and held in that position for 10 seconds. They were instructed that this was the target position they were to replicate, thus providing them with the proprioceptive information needed to identify the target location. Subjects were passively returned to the starting position before the beginning of active replication of the target position. The movable buttress was removed from the intended path of motion, so it would not interfere if motion exceeded the 27° of rotation.

**Visual Feedback**

Subjects were provided VF by monitor connected to a fourth video camera, independent of the motion analysis system, which enabled them to judge movement accuracy. The camera was located 3 m from the shoulder wheel apparatus, oriented with its lens-to-object axis parallel to the rotational axis of the shoulder wheel. The video monitor (38.1 cm di-
agional) for this separate camera was placed 2 m away from the subject in the frontal plane to provide real-time 2-dimensional VF of the retroreflective markers of the shoulder wheel and target during the VF condition. The video monitor was covered during the PF condition to eliminate the VF of the retroreflective markers and targets.

Protocol

Subjects performed JPS testing with and without an external load, defined as 5% body weight, in both the VF and PF conditions (see Figure 2A). Subjects were required to internally rotate 27° (75° of external rotation to 48° of external rotation) in order to replicate the fixed target (Figure 2B). Subjects were instructed to move at a comfortable speed for all 4 movement conditions (VF loaded, VF unloaded, PF loaded, and PF unloaded). A total of 32 trials were performed by each subject. Each trial was randomly assigned in a nonrepeating, counterbalanced fashion, to each of the 4 movement conditions, generating 8 trials per condition. This final arm and shoulder wheel apparatus position enabled the calculation of movement accuracy measures relative to the target position (CE, VE, and AE).

We calculated the mean of the 8 trials for each of the 4 movement conditions and used that value for statistical analysis. Breaks were typically provided after blocks of 10 to 20 repetitions, or on the subject’s request, and lasted 5 to 10 minutes. These frequent breaks were allowed to minimize the influence of muscular and mental fatigue. This procedure took approximately 1.5 hours to complete, as it was part of a larger study that included other movement conditions.24

Statistical Analysis

We calculated peak angular velocity of the movable arm of the shoulder wheel for all 4 movement conditions. Independent variables were the type of feedback (PF, VF) and presence or absence of the load (unloaded, loaded). Dependent variables included CE, VE, AE, and peak angular velocity.

Separate 2 × 2 fully repeated analyses of variance were performed to evaluate the effects of feedback and load on the CE, VE, AE, and peak angular velocity (version 11.5; SPSS Inc, Chicago, IL). The level of significance for each test was P < .05.

RESULTS

No significant interactions were noted between the 2 main conditions (type of feedback and the presence of a load) for CE (F1,19 = 0.22, P = .698, 1 − β = .666), VE (F1,19 = 1.21, P = .268, 1 − β = .181), or AE (F1,19 = 0.009, P = .925, 1 − β = .501) (Tables 1–3). Moreover, we found no significant interactions between the type of feedback and the presence of a load on peak angular velocity (F1,19 = 23.7, P = .421, 1 − β = .12) (Table 4).

No significant differences were seen between the main effect of loaded and unloaded movement accuracy as measured by CE (F1,19 = 0.27, P = .61, 1 − β = .08) and AE (F1,19 = 0.007, P = .94, 1 − β = .05) (see Tables 1 and 3). However, unloaded movements demonstrated significantly greater VE (F1,19 = 11.5, P = .003, 1 − β = .886) than loaded

Table 1. Constant Error of Movements With and Without a Load and Visual Feedback (*) (Mean ± SD)

<table>
<thead>
<tr>
<th></th>
<th>Visual Feedback</th>
<th>Proprioceptive Feedback</th>
<th>Main Effects (Loaded versus unloaded)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unloaded</td>
<td>−0.2 ± 0.5</td>
<td>3.7 ± 4.0</td>
<td>1.8 ± 2.4</td>
</tr>
<tr>
<td>Loaded</td>
<td>−0.1 ± 0.6</td>
<td>3.9 ± 3.9</td>
<td>1.9 ± 3.5</td>
</tr>
<tr>
<td>Main Effect</td>
<td>(Visual feedback versus proprioceptive feedback)</td>
<td>−0.1 ± 0.6*</td>
<td>8 ± 3.9</td>
</tr>
</tbody>
</table>

*Indicates significant difference between movements with visual and proprioceptive feedback (P < 0.05).

Table 2. Variable Error of Movements With and Without a Load and Visual Feedback (*) (Mean ± SD)

<table>
<thead>
<tr>
<th></th>
<th>Visual Feedback</th>
<th>Proprioceptive Feedback</th>
<th>Main Effects (Loaded versus unloaded)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unloaded</td>
<td>0.9 ± 0.5</td>
<td>3.1 ± 1.3</td>
<td>2.0 ± 0.7</td>
</tr>
<tr>
<td>Loaded</td>
<td>0.6 ± 0.2</td>
<td>2.5 ± 0.8</td>
<td>1.5 ± 0.4†</td>
</tr>
<tr>
<td>Main Effect</td>
<td>(Visual feedback versus proprioceptive feedback)</td>
<td>0.7 ± 0.4*</td>
<td>2.8 ± 0.2</td>
</tr>
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</table>

*Indicates significant difference between movements with visual and proprioceptive feedback (P < 0.05).
†Indicates significant difference between unloaded and loaded movements (P < 0.05).

Table 3. Absolute Error of Movements With and Without a Load and Visual Feedback (*) (Mean ± SD)

<table>
<thead>
<tr>
<th></th>
<th>Visual Feedback</th>
<th>Proprioceptive Feedback</th>
<th>Main Effects (Loaded versus unloaded)</th>
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</thead>
<tbody>
<tr>
<td>Unloaded</td>
<td>0.4 ± 0.3</td>
<td>4.6 ± 3.2</td>
<td>2.5 ± 3.1</td>
</tr>
<tr>
<td>Loaded</td>
<td>0.5 ± 0.5</td>
<td>4.6 ± 3.4</td>
<td>2.5 ± 3.2</td>
</tr>
<tr>
<td>Main Effect</td>
<td>(Visual feedback versus proprioceptive feedback)</td>
<td>0.5 ± 0.4*</td>
<td>4.6 ± 3.3</td>
</tr>
</tbody>
</table>

*Indicates significant difference between movements with visual and proprioceptive feedback (P < 0.05).

Table 4. Peak Rotational Velocity of Movements With and Without a Load and Visual Feedback (*) (Mean ± SD)

<table>
<thead>
<tr>
<th></th>
<th>Visual Feedback</th>
<th>Proprioceptive Feedback</th>
<th>Main Effects (Loaded versus unloaded)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unloaded</td>
<td>43.4 ± 3.1</td>
<td>52.1 ± 4.9</td>
<td>47.8 ± 3.6</td>
</tr>
<tr>
<td>Loaded</td>
<td>34.7 ± 1.3</td>
<td>38.9 ± 1.1</td>
<td>36.9 ± 1.0†</td>
</tr>
<tr>
<td>Main Effect</td>
<td>(Visual feedback versus proprioceptive feedback)</td>
<td>39.1 ± 2.0*</td>
<td>45.6 ± 2.9</td>
</tr>
</tbody>
</table>

*Indicates significant difference between movements with visual and proprioceptive feedback (P < 0.05).
†Indicates significant difference between unloaded and loaded movements (P < 0.05).
movements,signifying less consistency associated with these movements (see Table 2).

Movements were much less accurate and consistent in the PF than the VF condition; significant differences were demonstrated in CE ($F_{1,19} = 23.7, P < .001, 1 - \beta = 1.0$), VE ($F_{1,19} = 82.6, P < .001, 1 - \beta = 1.0$), and AE ($F_{1,19} = 35.9, P < .001, 1 - \beta = 1.0$) (see Tables 1–3).

Unloaded movements demonstrated greater ($F_{1,19} = 13.7, P = .003, 1 - \beta = .91$) peak rotational velocity (47.8 ± 8.37/s) than the loaded condition (36.9 ± 4.27/s). Movements for the PF condition demonstrated greater ($F_{1,19} = 4.9, P = .04, 1 - \beta = .55$) peak rotational velocity (45.6 ± 7.37/s) than the VF (39.1 ± 5.77/s) condition (see Table 4).

**DISCUSSION**

Our purpose was to examine the influence of an added external load on movement velocity, accuracy, and consistency in movements that used primarily PF and movements that used primarily PF Performance error was quantified by 3 measures (CE, VE, and AE) and peak rotation velocity was recorded for each movement. Although our main focus was not the difference between the VF and PF conditions, we include this comparison to examine the influence of added loads during JPS testing and movements with visual feedback.

Force sensation and position sense have been reported to be inextricably linked, suggesting a role for the GTO and muscle spindles during functional movements. After the target position was established with passive positioning, active movement was used to replicate the target in an effort to maximize the GTO influence on JPS, as the GTO operates more effectively with submaximal muscle activation. Light loads were also used in an effort to avoid fatigue. The presence of a load during PF movements, similar to JPS testing, had no significant effect on accuracy measured with CE and AE. Loaded movements demonstrated lower VE scores than unloaded movements (1.5 ± 0.4° and 2.0 ± 0.4°, respectively), indicating greater consistency in the ability of subjects to replicate the target. Added weight during PF movements was used to enhance GTO feedback during active movements during the study of shoulder JPS. Additional loads have been used to demonstrated enhanced elbow JPS. However, we are unable to directly compare our results with those of previous shoulder investigations, as there appear to be no other published studies on how additional loads affect shoulder JPS.

Another possible reason for the lack of a significant difference in accuracy as measured by CE and AE between the loaded and unloaded conditions could be the minimal influence of GTO feedback on human movement control compared with the influence of muscle spindle feedback. Additionally, the inhibition generated by the GTO typically occurs in an effort to avoid excess force against an external object or near end range, which we did not test. Our study was performed with subjects in an externally rotated position, whereas internal rotation movement releases tension within the anterior portion of the shoulder capsule, minimizing contributions from joint receptors. Additional loads for the VF and PF conditions generated slower peak rotational velocities. The Fitts law dictates that movement accuracy decreases linearly with faster movement speeds, whereas slower movements tend to be more accurate. Additional loads can dampen the initial peak velocity, which could make it easier to achieve target position. When movement accuracy and consistency are being evaluated, slower movements do not necessarily result in better performance. The complex interaction among multiple proprioceptive inputs that can influence the ability to accurately move to a target is beyond the scope of this study and warrants further investigation.

We report both the VF and PF conditions as a way to compare the influence of additional loads during these movements. The CE observed for the unloaded condition was between the 2.7° reported by Safran et al and the 6° reported by Lee et al. The 3.1° of VE we report for the unloaded condition is less than the 4° reported for passive external rotation by Janwantanakul et al and the 3.9° for internal rotation reported by Dover and Powers. The 4.6° of AE we report for the unloaded condition is between the 4.5° reported by Dover et al for internal rotation movements and the 6° reported by both Janwantanakul et al and Rogol et al for external rotation movements. Although methodological differences could account for these small differences in shoulder JPS outcomes, our data are consistent with those of previous studies.

We report differences in VE between the unloaded and loaded conditions, with no such difference in CE and AE. This is in agreement with the thought that CE and AE evaluate accuracy, whereas VE is more representative of the consistency of a performance. However, reporting CE also results in a directional bias to accuracy but not consistency, which is not encapsulated with AE. Overshooting a target tends to produce positive values for CE, demonstrated in this study during the PF movement condition, whereas undershooting produces negative values for CE. Clark et al contended that CE represents a systematic error, and this measure provides information about the “calibration” or “internal bias” of kinesthetic position sense. Clark et al also suggested that VE is better suited to represent overall performance of movements. Schmidt and Lee suggested that VE continues to improve with practice, whereas CE remains fairly constant for active movements. We believe that using 3 measures of a performance, such as CE, VE, and AE, increases the ability to identify subtle differences during shoulder JPS that could indicate differences in CNS feedback and subsequent movement control.

**STUDY LIMITATIONS**

Movements that include direct VF are referred to as the VF condition, and movements in the absence of vision are referred to as the PF condition. Although we acknowledge the presence of proprioceptive feedback during the VF condition, we categorized this condition according to the main feedback via vision.

It is unclear if a restricted single degree-of-freedom movement, such as glenohumeral internal rotation with the upper extremity contained within a shoulder wheel apparatus, has any application to movement accuracy during unrestricted upper extremity movements. If not, we could question all results from studies of single-joint measurements of joint kinesthesia in the upper extremity. Single-plane, restricted movements appear to bias measures of motor performance. However, it has not been demonstrated if performance measures from a movement restricted to a single degree of freedom have any significance on 3-dimensional functional movements. Additionally, we provided VF through a video monitor in 2-dimensional space, compared with the usual 3-dimensional VF.
encountered during normal daily function. Restricting movem-
ents to a single plane and providing 2-dimensional feedback
could limit the interpretations of this study. Moreover, we did
not calculate effect sizes a priori, but a post hoc analysis dem-
onstrated large effect sizes \( (d > 1) \) between the VF and PF
conditions and small effect sizes between the unloaded and
loaded conditions for CE \( (d = 0.03) \), VE \( (d = 0.38) \), and
AE \( (d = 0.0) \). These findings suggest that even though statisti-
cal significance was demonstrated in VE between the loaded
and unloaded conditions, small effect sizes require cautious
interpretation, with further study needed to corroborate the
outcomes observed here.

It is unclear if PF during active target replication is influ-
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CONCLUSIONS

Methods of assessing shoulder JPS when active movements
are used should include the addition of an extra load to in-
corporate the contributions of the GTO. Multiple measures of
performance, such as CE, VE, and AE, may be needed to fully
assess patient function. Although differences between loaded
and unloaded movements might result in subtle differences in
VE, future clinical testing is necessary to fully determine the
influence of external loads on active movements during should-
ner JPS tests. Additional research is required to determine the
CNS mechanisms behind active movements that rely on kin-
esthetic feedback and how an external load influences this type
of assessment.

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larger study that encompassed and examined other movement con-
ditions. Parts of these data were originally presented at the 55th
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REFERENCES

1. Lephart SM, Warner JR, Borsa PA, Fu FH. Proprioception of the shoulder
joint in healthy, unstable and surgically repaired shoulders. J Shoulder
2. Smith RL, Brunolli J. Shoulder kinesthesia after anterior glenohumeral
In: Kandel ER, Schwartz JH, eds. Principles of Neural Science. New
4. Rogol IM, Ernst G, Perrin DH. Open and closed kinetic chain exercises
improve shoulder joint reposition sense equally in healthy subjects. J Athl
5. Rothwell JC, Taub MM, Day BL, Obeso JA, Thomas PK, Marsden CD.
515–542.
6. Ghez C, Gordon J, Ghilardi MF. Impairments of reaching movements in
patients without proprioception, II: effects of visual information on ac-
7. Gordon J, Ghilardi MF, Ghez C. Impairments of reaching movements in
8. Carew TJ, Ghez C. Muscles and muscle receptors. In: Kandel ER,
9. Burgess PR, Wei JY, Clark FJ, Simon J. Signaling of kinesthetic infor-
mation by peripheral sensory receptors. Annu Rev Neurosci. 1982;5:171–
187.
10. MacEachern G, Gandevia SC, Burke D. Perceptual responses to microstimu-
lation of single afferents innervating joints, muscles and skin of the hu-
11. Burke D, Gandevia SC, MacEachern G. Responses to passive movement of
receptors in joint, skin and muscle of the human hand. J Physiol. 1988;
12. Millar J. Joint afferent fibres responding to muscle stretch, vibration and
13. Moberg E. The role of cutaneous afferents in position sense, kinesthesia,
14. Newton RA. Joint receptor contributions to reflexive and kinesthetic re-
15. Houk JC, Henneman E. Responses of Golgi tendon organs to active con-
481.
16. Crago PE, Houk JC, Rymer WZ. Sampling of total muscle force by ten-