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ORIGINAL RESEARCH REPORT

The Effect of Target Position on the Accuracy of Cervical-Spine-Rotation Active Joint-Position Sense

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Context: The cervical spine can be divided into upper and lower units, each making a different contribution to the magnitude of rotation and proprioception. However, few studies have examined the effect of the cervical-rotation positions on proprioception. ***Objective:*** To compare cervical-spine rotation active joint-position sense (AJPS) near midrange of motion (mid-ROM; 30°) and near end-ROM (60°). ***Design:*** Cross-sectional study. ***Setting:*** Human performance research laboratory. ***Participants:*** 53 military helicopter pilots (age 28.4 ± 6.2 y, height 175.3 ± 9.3 cm, weight 80.1 ± 11.8 kg). ***Main Outcome Measures:*** A motion-analysis system was used to record cervical-rotation kinematics. Subjects sat in a chair wearing a headband and blindfold. First, they actively rotated the head right or left to a target position (30°/60°), with real-time verbal cues provided by the tester. Subjects held the target position for 5 s and then returned to the start position. After this, they replicated the target position as closely as possible. Five trials were performed in both directions to both target positions (R30/R60/L30/L60). Order of direction/position was randomized. The difference between target and replicated positions was calculated and defined as absolute error (AE), and the mean of 5 trials was used for analyses. Wilcoxon signed-ranks tests were used to compare AJPS at the different target positions ($P < .0125$ with Bonferroni adjustments). ***Results:*** End-ROM AEs were significantly more accurate than mid-ROM AEs ($P = .001$). ***Conclusion:*** Cervical-spine-rotation AJPS is more accurate near end-ROM than mid-ROM. Both target positions should be used to examine cervical-spine-rotation AJPS of both the upper and lower units.

Keywords: proprioception, neck, helicopter pilots

Normal postural alignment and human movement depend on effective and efficient sensorimotor control.[1] This means that before the central nervous system can generate effective and efficient motor output, appropriate sensory input is required.[2] Proprioception is the sensory component of sensorimotor control and directly mediates feedforward and feedback neuromuscular control of joint stability.[3–5] With regard to the cervical spine, proprioceptive information from joint and muscle mechanoreceptors is integrated with vestibular and visual feedback to control head position, head orientation, and whole-body posture.[6,7] Proprioception is a component of the sensorimotor system and plays an important role in maintaining joint stability.[8,9] Because proprioception plays a critical role in the sensorimotor control of joint stability, an understanding of cervical-spine proprioception is important for determining the pathoetiology of neck pain and the design and implementation of targeted intervention programs for the prevention and rehabilitation of neck pain.

Past work has demonstrated that cervical-spine proprioception can be impaired in individuals with neck pain when compared with individuals without neck pain. Heikkilä and Wenngren[10] reported that patients with a history of traumatic neck pain had significantly less-accurate cervical-spine kinesthetic sensibility with a transverse-plane head-repositioning task than control subjects. Rix and Bagust[11] reported that patients with a history of nontraumatic neck pain had significantly less-accurate cervical-spine kinesthesia with a sagittal-plane head-relocation task than control subjects. On the other hand, other studies that used an outcome measure similar to that of the current study found no proprioceptive deficit in individuals with a history of neck pain or whiplash.[12–14] Panjabi[9,15] discussed how dysfunction/disruption of appropriate proprioceptive feedback can affect coordinated activation of skeletal muscles and contribute to chronic spinal-pain syndromes.

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Previous research on different joints has consistently demonstrated significantly less proprioceptive acuity near the middle of a joint's anatomical range of motion (ROM) than near a joint's end-ROM.[16–21] The cervical spine can be anatomically and biomechanically divided into the upper and lower cervical spine,[22–24] with the first 40° to 45° of left and right rotation predominantly occurring at the C1–C2 level, after which rotation is progressively taken up by each descending motion segment.[22,25] To our knowledge, there is only 1 published study that examined cervical-spine-rotation proprioception at different angles in 1 plane of motion.[26] Loudon et al[26] evaluated cervical-spine-rotation active joint-position sense (AJPS) using left and right rotation to target angles of 30° and 50°. Individuals with a history of whiplash injury were compared with age-matched subjects without a history of neck pain. Results revealed that those with whiplash injury were significantly less accurate in replicating target angles than were the control subjects. The study did not, however, investigate potential differences in AJPS within each group of subjects at the different target angles.

Therefore, the purpose of the study was to compare cervical-spine left- and right-rotation AJPS near mid-ROM (30°) and near end-ROM (60°). AJPS at 30° was intended to focus on proprioception of the upper cervical spine, and AJPS at 60° was intended to include proprioception of the upper and lower cervical spines. We hypothesized that AJPS would be significantly more accurate near end-ROM than mid-ROM due to loading of a larger quantity of musculoskeletal tissues and the resulting greater mechanoreceptor stimulation. It may be clinically important to determine if there are positional differences in cervical AJPS to consider whether ROM-specific proprioception testing and training programs may need to be included in comprehensive interventions planned to reduce the incidence and severity of neck pain in individuals with a history of neck pain or whiplash.

Methods

Design

This study was a cross-sectional design. As part of larger ongoing injury-prevention and performance-optimization research initiatives, each subject visited once for a 2-hour testing session.

Participants

Human-subjects research approval was obtained from the Dwight D. Eisenhower Army Medical Center and the university institutional review boards. Active-duty military helicopter pilots from the 101st Airborne Division (Air Assault) were recruited. Inclusion criteria were age 18 to 55 years and being active-duty military helicopter pilots. Exclusion criteria were cardiovascular, pulmonary, neurological, balance, or metabolic disorder; skin allergy to adhesive tape; a history of concussion, mild head injury, or neck pain in the previous 12 months; current spinal, upper-limb, or lower-limb impairments that could affect test performance; pain at the time of testing; or restriction on physical training. A total of 53 subjects (5 women and 48 men) participated in this investigation (age 28.4 ± 6.4 y, height 175.3 ± 9.8 cm, and 80.1 ± 11.8 kg). All subjects provided written informed consent before participation in this study.

Procedures

Subjects reported to the human performance research laboratory at Fort Campbell, Kentucky. Cervical-spine proprioception was measured by AJPS testing (active replication of initial active positioning) using the Vicon Nexus motion-capture system synchronized with 6 wall-mounted MX13+ infrared cameras (Vicon Motion Systems, Centennial, CO). In our laboratory, the accuracy of the Vicon Nexus system is 0.39 mm translation and 0.08° rotation.

First, subjects were blindfolded and seated face forward on a wooden chair with hips and knees positioned at approximately 90° flexion and feet hip-width apart. The elbows and forearms were supported by cushions on top of the chair armrests to elevate the shoulder girdle approximately 2.5 cm, off-load the cervical spine from the weight of the upper limbs, and reduce tension in the neck–shoulder musculotendinous tissues. This was intended to bias mechanical loading to tissues surrounding the cervical vertebrae themselves. Subjects wore a 5-cm-wide black athletic headband aligned parallel with the Frankfort plane[27] (Figure 1). Retroreflective markers were placed over the midline of the sphenoid bone (temple) and the most posterior aspect of the parietal bone on both sides of the head in line with the longitudinal midline of the headband (4 head markers) and over the C7 and T10 spinous processes, the jugular notch, and the xiphoid process.

Before testing, a static calibration trial was performed to create a subject-specific head-on-trunk model in the Vicon Nexus software. Full left and right cervical-rotation active-ROM trials were performed 3 times to ensure that subjects had more than 60° of motion available. During testing, the examiner used standardized verbal cues to instruct the subject to rotate toward the desired 30° or 60° left/right-rotation target position. The testing order was randomly assigned for each subject. Subjects performed 1 target-position trial followed by 1 replication trial. Using real-time feedback from the Vicon Nexus, the examiner cued the subject to hold the target position for 5 seconds. Subjects were asked to concentrate on feeling where their head was in space, and then return to the face-forward position. After a 5-second pause, subjects were instructed to replicate the target angle and then press a trigger to mark that point in the motion-capture system. The same procedures were repeated 5 times. The examiner visually inspected the subjects' motion to verify that the correct plane of motion was used throughout ROM.

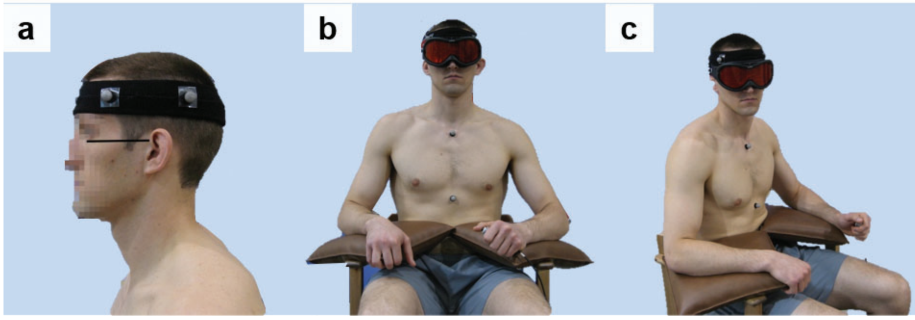

Figure 1 — Cervical-spine proprioception testing. (a) Headband-marker configuration and Frankfort plane (black line). (b) Subject positioning. (c) Active rotation to target angle.

Kinematic data were processed and filtered in the Vicon Nexus software using a Woltring filter.[28] Cervical-rotation angles from the biomechanical model were computed using Euler angles and reported as the rotational position of the head segment relative to the trunk segment in the *z*-axis of the trunk (degrees). Cervical-rotation data from each trial were exported into separate data files, and a custom-written Matlab program (MathWorks, Inc, Natick, MA) was used to compute the dependent variables of this study.

Cervical-spine-rotation AJPS has previously been reported using absolute error (AE), constant error (CE), and variable error (VE). AE omits the direction of error and simply describes the magnitude of error, CE describes the magnitude and direction (underestimation or overestimation) of error, and VE is the standard deviation of the CE across trials.[6,29] Based on our preliminary reliability study (Table 1), the AE had fair to substantial reliability[30] and was used in the current investigation.

Statistical Analyses

All statistical analyses were performed using IBM SPSS software (version 20.0, IBM Corp, Armonk, NY). Descriptive statistics were calculated for all variables. The Shapiro-Wilk test showed that most variables were not normally distributed. Therefore, pairwise Wilcoxon signed-ranks tests were performed to determine which positions were significantly different. Alpha was set to .0125 with Bonferroni adjustments a priori.

Results

All subjects had sufficient active ROM to perform the cervical AJPS 60° test. The mean (± SD) active ROM was 71.1° ± 6.1° to the right and 73.4° ± 6.6° to the left. AE at R30 was significantly larger than the AE at R60 (R30 3.0° ± 1.3°, R60 2.2° ± 1.0°, P = .001) and the AE at L60 (R30 3.0° ± 1.3°, L60 2.2° ± 1.2°, P = .001). Similarly, AE at L30 was significantly larger than the AE at R60 (L30 3.2° ± 1.6°, R60 2.2° ± 1.0°, P = .001) and the AE at L60 (L30 3.2° ± 1.6°, L60 2.2° ± 1.2°, P = .001). There was no significant difference between the AEs at R30 and L30 (R30 3.0° ± 1.3°, L30 3.2° ± 1.6°, P = .145) and those at R60 and L60 (R60 2.2° ± 1.0°, L60 2.2° ± 1.2°, P = .892).

Table 1 Intrarater Reliability and Precision for Cervical Joint-Position Sense

Absolute error	$ICC_{2,1}$	Standard error of the mean
R30° target	.52	1.3°
R60° target	.44	1.0°
L30° target	.81	0.6°
L60° target	.76	0.6°

Discussion

The current study has demonstrated better AE near end-ROM versus mid-ROM, so our hypothesis was supported. The AE values from the current study are consistent with previous work.[29] The current results are also in agreement with previous studies of peripheral joints that indicated better proprioception near end-ROM than mid-ROM.[16–21]

There are potential explanations as to why subjects demonstrated significantly better proprioception near end-ROM versus mid-ROM. One explanation considers the cervical joints and the contribution of capsuloligamentous and intervertebral disc mechanoreceptors that are prevalent in the human cervical spine.[31,32] With right rotation of 40° to 45°, for example, the capsules of the right and left C1–C2 apophyseal joints are stretched along with the left alar ligament.[22,33,34] With rotation beyond 45°, the capsules of the right and left apophyseal joints from the C2–C3 level to the C7–T1 level are progressively stretched.[23,25] Thus, with increasing rotation beyond 45° more apophyseal joint capsules and intervertebral discs are loaded, likely resulting in stimulation of a greater number of mechanoreceptors.

Another explanation considers the cervical muscles and the contribution of muscle spindles. Morphologically, the cervical muscles contain more muscle spindles (higher density) than other muscles in the body to play a critical role in vestibular-visual coordination and postural control.[35,36] Furthermore, deep cervical flexor muscles (the longus colli) contain more muscle spindles than deep cervical extensor muscles (multifidus), as the deep flexors maintain the head in slightly flexed position and keep the head and the cervical spine aligned, while the deep extensors mostly resist gravity.[37] With right rotation of 40° to 45°, the ipsilateral rectus capitis posterior major and obliquus capitis inferior are the main agonists for motion between C1 and C2.[25] With rotation beyond 45°, the ipsilateral longus colli and contralateral scalenes and sternocleidomastoid are recruited as agonists for motion extending below C2.[25,38] Because alpha-gamma coactivation and stimulation of the muscle spindle always occur with active movements,[39] the more agonists that are recruited for a task the more muscle spindles that are likely stimulated via alpha-gamma coactivation. More antagonist muscle mechanoreceptors might also be stimulated, as active ROM increases beyond 45° as more antagonists are stretched.

Further explanation considers the human fascia, which also contains mechanoreceptor nerve endings.[40,41] As active ROM increases from near mid-ROM to end-ROM, it is likely that more mechanoreceptors are stimulated due to an increase in tissue stretch surrounding the cervical spine. This increase in afferent information near end-ROM may ultimately result in higher precision in position sense than near mid-ROM.

Another potential explanation considers the involvement of the vestibular system. In the current investigation, subjects took 5.1 seconds and 6.0 seconds to reach the target positions near mid-ROM and end-ROM, respectively. The head-rotation velocity is well above the mean motion-detection threshold (0.46°/s) of the vestibular threshold (during using the passive whole-body-rotation testing).[42] In other words, the vestibular system is likely contributing to cervical-spine AJPS. In addition, the vestibular system becomes more sensitive at higher velocity.[43] Note that in the current study subjects moved their head faster when aiming for the near-end-ROM targets. Therefore, from the perspective of the vestibular system, the differences in head speed between mid-ROM and end-ROM may explain the differences in the AEs. On the other hand, there are reports on the inhibition of vestibular signals with active head movements.[44] Unfortunately, the current investigation cannot rule out one explanation over others; however, it is important to recognize the potential role of the vestibular system during cervical-spine AJPS testing.

There are limitations in the study. First, all subjects were active-duty military helicopter pilots. The current findings may be specific to this population and lack the generalizability. Second, the AJPS is inheritably difficult for subjects to perform consistently, as demonstrated in a wide range of reliability, precision, and normality data; therefore, the current findings must be interpreted cautiously. We do support the current findings, as the variables that reached statistical significance have large effect size (0.64–0.71) and sufficient power (>.99).

Clinically, it is as yet unknown whether the absolute size of such differences have the potential to be clinically significant. Considering, for example, that the mean ROM for most motion segments of the lower cervical spine (C2–T1) is less than 6.5°,[45] proprioceptive errors of just 1° or 2° represent a major proportion of the available anatomical ROM and may induce subtle joint malalignment that results in aberrant cervical motion-segment load transfer. Subtle cervical-spine joint malalignments, or "positional faults" as termed by the positional fault hypothesis,[46] are certainly implicated and widely considered clinically meaningful phenomena in cervical syndromes associated with nontraumatic onset of pain.[47,48] This work reports that statistically significant differences exist at 2 different positions in the available cervical-spine left/right-rotation active ROM, and, therefore, an aim of future investigations could be to determine whether the absolute size of differences reported in this study has the potential to be clinically significant in injury control for nontraumatic neck pain in military helicopter pilots.

Conclusions

Cervical-spine-rotation AJPS was more accurate near end-ROM than near mid-ROM. Because there were significant differences in cervical-spine-rotation AJPS at different points in the right/left-rotation ROM, both target positions should be examined to fully encompass right/left AJPS of both the upper and lower cervical spine. Use of both mid- and end-ROM target positions would likely provide a thorough cervical-spine transverse-plane proprioception profile. The findings of this study are clinically important because they highlight ROM-specific differences in cervical-spine-rotation AJPS. Range-of-motion-specific proprioception testing may be considered for the prospective identification of risk factors for neck pain in civilian athletes and/or military helicopter pilots.

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References

1. Shumway-Cook A, Woollacott M. *Motor Control: Theory and Practical Applications*. 2nd ed. Philadelphia, PA: Lippincott Williams & Wilkins; 2000.
2. Ghez C, Hening W, Gordon J. Organization of voluntary movement. *Curr Opin Neurobiol*. 1991;1(4):664–671. PubMed doi:10.1016/S0959-4388(05)80046-7
3. Riemann BL, Lephart SM. The sensorimotor system, part I: the physiologic basis of functional joint stability. *J Athl Train*. 2002;37(1):71–79. PubMed

4. Riemann BL, Lephart SM. The sensorimotor system, part II: the role of proprioception in motor control and functional joint stability. *J Athl Train*. 2002;37(1):80–84. PubMed
5. 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(1):130–137. PubMed doi:10.1177/036354659702500126
6. Armstrong B, McNair P, Taylor D. Head and neck position sense. *Sports Med*. 2008;38(2):101–117. PubMed doi:10.2165/00007256-200838020-00002
7. Kristjansson E, Treleaven J. Sensorimotor function and dizziness in neck pain: implications for assessment and management. *J Orthop Sports Phys Ther*. 2009;39(5):364–377. PubMed doi:10.2519/jospt.2009.2834
8. Lephart SM, Riemann BL, Fu FH. Introduction to the sensorimotor system. In: Lephart SM, Fu FH, eds. *Proprioception and Neuromuscular Control in Joint Stability*. Champaign, IL: Human Kinetics; 2000:xvii–xxiv.
9. Panjabi MM. The stabilizing system of the spine: part I: function, dysfunction, adaptation, and enhancement. *J Spinal Disord*. 1992;5(4):383–389. PubMed doi:10.1097/00002517-199212000-00001
10. Heikkilä HV, Wenngren BI. Cervicocephalic kinesthetic sensibility, active range of cervical motion, and oculomotor function in patients with whiplash injury. *Arch Phys Med Rehabil*. 1998;79(9):1089–1094. PubMed doi:10.1016/S0003-9993(98)90176-9
11. Rix GD, Bagust J. Cervicocephalic kinesthetic sensibility in patients with chronic, nontraumatic cervical spine pain. *Arch Phys Med Rehabil*. 2001;82(7):911–919. PubMed doi:10.1053/apmr.2001.23300
12. Teng CC, Chai H, Lai DM, Wang SF. Cervicocephalic kinesthetic sensibility in young and middle-aged adults with or without a history of mild neck pain. *Man Ther*. 2007;12(1):22–28. PubMed doi:10.1016/j.math.2006.02.003
13. Grip H, Sundelin G, Gerdle B, Karlsson JS. Variations in the axis of motion during head repositioning—a comparison of subjects with whiplash-associated disorders or non-specific neck pain and healthy controls. *Clin Biomech (Bristol, Avon)*. 2007;22(8):865–873. PubMed doi:10.1016/j.clinbiomech.2007.05.008
14. Kristjansson E, Dall'Alba P, Jull G. A study of five cervicocephalic relocation tests in three different subject groups. *Clin Rehabil*. 2003;17(7):768–774. PubMed doi:10.1191/0269215503cr676oa
15. Panjabi MM. A hypothesis of chronic back pain: ligament subfailure injuries lead to muscle control dysfunction. *Eur Spine J*. 2006;15(5):668–676. PubMed doi:10.1007/s00586-005-0925-3
16. Allegrucci M, Whitney SL, Lephart SM, Irrgang JJ, Fu FH. Shoulder kinesthesia in healthy unilateral athletes participating in upper extremity sports. *J Orthop Sports Phys Ther*. 1995;21(4):220–226. PubMed doi:10.2519/jospt.1995.21.4.220
17. Borsa PA, Lephart SM, Irrgang JJ, Safran MR, Fu FH. The effects of joint position and direction of joint motion on proprioceptive sensibility in anterior cruciate ligament-deficient athletes. *Am J Sports Med*. 1997;25(3):336–340. PubMed doi:10.1177/036354659702500311
18. Janwantanakul P, Magarey ME, Jones MA, Dansie BR. Variation in shoulder position sense at mid and extreme range of motion. *Arch Phys Med Rehabil*. 2001;82(6):840–844. PubMed doi:10.1053/apmr.2001.21865
19. Allison GT, Fukushima S. Estimating three-dimensional spinal repositioning error: the impact of range, posture, and number of trials. *Spine*. 2003;28(22):2510–2516. PubMed doi:10.1097/01.BRS.0000090821.38624.D5
20. Lephart SM, Kocher MS, Fu FH, Borsa PA, Harner CD. Proprioception following anterior cruciate ligament reconstruction. *J Sport Rehabil*. 1992;1(3):188–196.
21. Lephart SM, Warner JJ, Borsa PA, Fu FH. Proprioception of the shoulder joint in healthy, unstable, and surgically repaired shoulders. *J Shoulder Elbow Surg*. 1994;3:371–380. PubMed doi:10.1016/S1058-2746(09)80022-0
22. Bogduk N, Mercer S. Biomechanics of the cervical spine. I: normal kinematics. *Clin Biomech (Bristol, Avon)*. 2000;15(9):633–648. PubMed doi:10.1016/S0268-0033(00)00034-6
23. Moroney SP, Schultz A, Miller J, Andersson G. Load-displacement properties of lower cervical spine motion segments. *J Biomech*. 1988;21(9):769–779. PubMed doi:10.1016/0021-9290(88)90285-0
24. Panjabi M, Dvorak J, Duranceau J, et al. Three-dimensional movements of the upper cervical spine. *Spine*. 1988;13(7):726–730. PubMed doi:10.1097/00007632-198807000-00003
25. Neumann D. *Kinesiology of the Musculoskeletal System*. St Louis, MO: Mosby; 2002.
26. Loudon JK, Ruhl M, Field E. Ability to reproduce head position after whiplash injury. *Spine*. 1997;22(8):865–868. PubMed doi:10.1097/00007632-199704150-00008
27. Lohman T, Roche A, Martorell R. *Anthropometric Standardization Reference Manual*. Champaign, IL: Human Kinetics; 1988.
28. Woltring HJ. Smoothing and differentiation techniques applied to 3-dimensional data. In: Allard P, Stokes IAF, Blanchi J-P, eds. *Three-Dimensional Analysis of Human Movement*. Champaign, IL: Human Kinetics; 1994.
29. Lee HY, Teng CC, Chai HM, Wang SF. Test–retest reliability of cervicocephalic kinesthetic sensibility in three cardinal planes. *Man Ther*. 2006;11(1):61–68. PubMed doi:10.1016/j.math.2005.03.008
30. Shrout PE. Measurement reliability and agreement in psychiatry. *Stat Methods Med Res*. 1998;7(3):301–317. PubMed doi:10.1191/096228098672090967
31. Mendel T, Wink C, Zimny M. Neural elements in human cervical intervertebral discs. *Spine*. 1992;17(2):132–135. PubMed doi:10.1097/00007632-199202000-00002
32. McLain RF. Mechanoreceptor endings in human cervical facet joints. *Spine*. 1994;19(5):495–501. PubMed doi:10.1097/00007632-199403000-00001
33. Dvorak J, Panjabi M. Functional anatomy of the alar ligaments. *Spine*. 1987;12(2):183–189. PubMed doi:10.1097/00007632-198703000-00016
34. Panjabi M, Dvorak J, Crisco JJ, Oda T, Wang P, Grob D. Effects of alar ligament transection on upper cervical

spine rotation. *J Orthop Res*. 1991;9(4):584–593. PubMed doi:10.1002/jor.1100090415

35. Kulkarni V, Chandy M, Babu K. Quantitative study of muscle spindles in suboccipital muscles of human foetuses. *Neurol India*. 2001;49(4):355–359. PubMed
36. Liu JX, Thornell L, Pedrosa-Domellöf F. Muscle spindles in the deep muscles of the human neck: a morphological and immunocytochemical study. *J Histochem Cytochem*. 2003;51(2):175–186. PubMed doi:10.1177/002215540305100206
37. Boyd-Clark LC, Briggs CA, Galea MP. Muscle spindle distribution, morphology, and density in longus colli and multifidus muscles of the cervical spine. *Spine*. 2002;27(7):694–701. PubMed doi:10.1097/00007632-200204010-00005
38. Kendall F, McCreary E, Provance P, Rodgers M, Romani W. *Muscles. Testing and Function*. 5th ed. Baltimore, MD: Lippincott, Williams & Wilkins; 2005.
39. Gordon J, Ghez C. Muscle receptors and spinal reflexes: the stretch reflex. In: Kandel E, Schwartz J, Jessell T, eds. *Principles of Neural Science*. 3rd ed. London, UK: Prentice-Hall; 1991:564–580.
40. Yahia L, Rhalmi S, Newman N, Isler M. Sensory innervation of human thoracolumbar fascia: an immunohistochemical study. *Acta Orthop Scand*. 1992;63(2):195–197. PubMed doi:10.3109/17453679209154822
41. Stecco C, Gagey O, Belloni A, et al. Anatomy of the deep fascia of the upper limb: second part: study of innervation. *Morphologie*. 2007;91(292):38–43. PubMed doi:10.1016/j.morpho.2007.05.002
42. Mallery RM, Olomu OU, Uchanski RM, Militchin VA, Hullar TE. Human discrimination of rotational velocities. *Exp Brain Res*. 2010;204(1):11–20. PubMed doi:10.1007/s00221-010-2288-1
43. Grabherr L, Nicoucar K, Mast FW, Merfeld DM. Vestibular thresholds for yaw rotation about an earth-vertical axis as a function of frequency. *Exp Brain Res*. 2008;186(4):677–681. PubMed doi:10.1007/s00221-008-1350-8
44. Cullen KE. Sensory signals during active versus passive movement. *Curr Opin Neurobiol*. 2004;14(6):698–706. PubMed doi:10.1016/j.conb.2004.10.002
45. Penning L, Wilmink JT. Rotation of the cervical spine: a CT study in normal subjects. *Spine*. 1987;12(8):732–738. PubMed doi:10.1097/00007632-198710000-00003
46. Vicenzino B, Paungmali A, Teys P. Mulligan's mobilization-with-movement, positional faults and pain relief: current concepts from a critical review of literature. *Man Ther*. 2007;12(2):98–108. PubMed doi:10.1016/j.math.2006.07.012
47. Hearn A, Rivett DA. Cervical SNAGs: a biomechanical analysis. *Man Ther*. 2002;7(2):71–79. PubMed doi:10.1054/math.2002.0440
48. Exelby L. The Mulligan concept: its application in the management of spinal conditions. *Man Ther*. 2002;7(2):64–70. PubMed doi:10.1054/math.2001.0435