

Comparison of Cervical Musculoskeletal Kinematics in Two Different Postures of Primate During Voluntary Head Tracking

Hyeonki Choi*

*School of Mechanical Engineering, Sungkyunkwan University,
300 Chunchun-dong, Jangan-gu, Suwon 440-746, Korea*

Emily Keshner

Sensory Motor Performance Program, Rehabilitation Institute of Chicago, Chicago, IL, USA

Barry W. Peterson

Department of Physiology, Northwestern University Medical School, Chicago, IL, USA

We have examined the effect on neck-muscle activation of altering whole body posture. A Rhesus monkey (*Macaca mulatta*) was trained to produce sinusoidal (0.25 Hz) head tracking movements in the sagittal plane when seated with trunk and head vertical or while standing in the quadrupedal position. Video-fluoroscopic images of cervical vertebral motion, and electromyographic (EMG) responses were recorded simultaneously. Results demonstrated that vertebral motion varied with body posture, occurring synchronously between all joints in the upright position and primarily at skull-C₁ when in the quadrupedal position. Muscle EMG activation was significantly greater ($p < 0.001$) in the quadrupedal position than when upright for all muscles except semispinalis cervicis. Peak activation of all the muscles occurred prior to peak head extension in the quadrupedal position, suggesting synchronous activity between muscles. Data suggest that, when upright, muscles were activated in functional groupings defined by their anatomical arrangement. In the quadrupedal position, gravity acting on the horizontally oriented head produced greater activation and a collective response of the muscles.

Key Words : Neck Musculature, Cervical Kinematics, Different Postures, Primate, EMG, Video-fluoroscopy

Nomenclature

C₁ : The 1st cervical vertebra
C₂ : The 2nd cervical vertebra
C₃ : The 3rd cervical vertebra
C₄ : The 4th cervical vertebra
C₅ : The 5th cervical vertebra
C₆ : The 6th cervical vertebra
C₇ : The 7th cervical vertebra
T₁ : The 1st thoracic vertebra

1. Introduction

Complex multiple muscle systems have the potential for producing single movements with variable muscle activation patterns. Neural and mechanical redundancies in the head-neck complex potentially provide great flexibility for producing head and neck movements. Longer neck muscles cross many cervical vertebrae and can generate moments about both lower and upper cervical joints. Overall, the number of independently controlled muscle elements (including subdivisions of compartmentalized muscles) exceeds the number of degrees of freedom of neck motion.

There is evidence that redundancies in either

* Corresponding Author.

E-mail : chk@me.skku.ac.kr

TEL : +82-31-290-7455; **FAX :** +82-31-290-5849

School of Mechanical Engineering, Sungkyunkwan University, 300 Chunchun-dong, Jangan-gu, Suwon 440-746, Korea. (Manuscript **Received** November 11, 2002; **Revised** May 24, 2003)

the neural or mechanical systems can be responsible for the variability in muscle selection. Keshner et al. (1997) hypothesized that spatial patterns of muscle activity in cats were variable because cervical joint mobility could produce alterations in the moment arms and force-generating capacity of the muscles. But only in some cases could biomechanical factors account for differences in the muscle activation patterns. At other times, different muscle activation patterns were observed without concomitant changes in muscle moment arms or force-generating potential. Neural factors are also responsible for the selection of muscle activation patterns which have been found to differ in cats depending on whether the animal was producing a reflex or voluntary head movement (Keshner et al., 1992). Runciman and Richmond (1997) cited body posture as a determining factor for variability in the moment arm and pulling direction of certain neck muscles. Thomson et al. (1994) found that during rotation of the head with different orientations of the cervical spine, some neck muscles varied their patterns of activity while others maintained a consistent pattern of activation.

Despite this opportunity for response variability, our previous work in both humans (Keshner et al., 1989) and cats (Keshner et al., 1992; Keshner et al., 1997) suggests that, within an animal, the CNS programs neck muscles to respond in specific directions rather than generating an infinite variety of muscle patterns. The selection of these particular activation patterns could be shaped by previous experience or be the result of anatomical and biomechanical constraints on the movement. The purpose of this study was to examine the effect of anatomical constraints by testing a repetitive head tracking task in the sagittal plane when the spine was either in a vertical (upright seated) or horizontal (quadrupedal) position.

2. Methods

2.1 Behavioral training

An adult male (7.7 kg) Rhesus monkey, *Macaca mulatta*, was trained, using positive

reinforcement, to perform sinusoidal (0.25 Hz) head tracking movements with an excursion of $\pm 20^\circ$ in the vertical (pitch) plane as he used a head-mounted laser to follow a green cross projected by a laser mirror-galvanometer system. In the first series of experiments, the monkey was seated in an upright posture within a Plexiglas box that enclosed his whole body below the neck. In the second series, the monkey stood in a quadrupedal position within the box. In both positions, the monkey's head and neck projected through a cloth collar covering an opening in the box, thus permitting full and free motion of the head and cervical spine. The monkey was required to sit or stand quietly, and to follow for 30 sec without interruption the green cross with a red spot projected by a laser attached to a connector atop his head. A second laser attached to the same connector projected a red line that allowed us to record a video image of roll orientation of the head.

2.2 Surgery

All surgical procedures were performed under halothane (1%) and nitrous oxide (80% N₂O, 20% O₂) anesthesia. Initially, a metal socket to hold the lasers and head velocity sensor was attached to the head with screws and dental acrylic. On completion of behavioral training, a second surgery was done to implant intramuscular wire electrodes in twelve muscles of the neck and to attach radio-opaque markers (tantalum washers) to spinous processes of the C₁, C₂, C₅, and C₇ vertebrae. Muscles from which we observed reliable modulation during pitch head motions included left biventer cervicis (BC), complexus (COM), levator scapular anterior (LSA), obliquus capitis inferior (OCI), rectus capitis posterior major (RCmaj), rectus capitis posterior minor (RCmin), rhomboideus capitis (RhCap), semispinalis cervicis (SSC), splenius capitis (SPL), and sternocleidomastoid (SCM). Electrode wires were threaded to a multipin connector cemented posteriorly on the skull.

2.3 Video motion and EMG analysis

Videofluoroscopic data were recorded (sam-

pling rate 30 Hz) directly on an S-VHS videotape (Panasonic model AG 7750, Hi-Fi Professional/Industrial Video System). Data included a sagittal view of the monkey from occiput to the T₁ vertebrae, a video image of the green target cross, and red laser spot and line, and a videocounter signal (Thalner Electronics, Inc). During recording, the behavior of the animal was also monitored on a standard television monitor. Three-dimensional head movements were measured by a triaxial angular rate sensor (Watson Industries, WI) attached to the connector on the head. During each trial, 8 channels of full-wave rectified, low-pass filtered (time constant 5 ms) EMG data, the target position signal, and angular rate signals of the head were collected at 200 Hz on a Macintosh computer which also generated the sinusoidal output controlling the laser galvanometer. Signals were stored in digital form for later reduction and analysis. Activation patterns of SPL were plotted against those of COM, the muscle lying directly beneath, and the lack of a significant relationship between the two signals implied no significant crosstalk.

A computer based video-motion analysis system (NIH Image) was employed to derive the x-y coordinates of vertebral reference points every 333 ms. Tantalum washers inserted during surgery assisted vertebral localization. The angular orientation of each vertebra was measured with respect to the C₇ vertebra. C₇ was used because T₁ was sometimes not visible due to the limited image size of the fluoroscope. The mean motion between C₇ and T₁ where both were visible was then used to transform our final average measurements to be relative to T₁. Angles with respect to C₇ were obtained by calculating the slope of a line between two points on each vertebral body and calculating the angle formed by the intersection of the lines for each vertebra with that of C₇. Changes in these angles between successive frames constituted the range of motion. These data were averaged across 2 stimulus cycles (8 sec) for smoothing. A Fast Fourier Transform (FFT) was performed on smoothed vertebral position data relative to T₁ to obtain real and imaginary values. Response timing (i.e., phase= \arctan [im-

aginary/real]) was calculated relative to position of the target and averaged across trials. A 2×8 repeated measures ANOVA and Tukey-Kramer post-hoc comparisons ($p < 0.05$) was used to examine differences in vertebral excursion across 20 trials of each body position and 10 trials of vertebral phase responses in each position.

A FFT was performed on the target position signal and muscle EMG responses to obtain real and imaginary values. Response timing (phase) and EMG response amplitudes (square root of the sum of the squared real and imaginary values) were then calculated. To derive meaningful EMG response gains, muscle EMG amplitudes were normalized to the average muscle EMG amplitude from three trials in which the animal was encouraged to produce a vigorous head shaking threat response in the frontal plane, thereby eliciting large voluntary EMG activity. Coherence between the EMG response and target position was calculated. EMG response phases were calculated relative to position of the target. According to our phase conventions peak up position was 0°, peak down was 180°, -90° was peak downward velocity, and +90° was peak upward velocity. A MANOVA was performed on at least eight trials of data from each muscle with response gains and phases from each trial as the dependent variables. Scheffe post-hoc comparisons ($p < 0.05$) examined the dependent variables across the two positions. Because we had only three trials of data in upright for LSA, a non-parametric Mann-Whitney *U* statistic ($p < 0.01$) was used to examine differences between these gains and phases across body positions.

3. Results

3.1 Vertebral motion in the two postures

As shown by Fig. 1, vertebral motion differed in the two body positions. Since excursions were referred to T₁, they tended to increase progressively when ascending from C₇ to skull. Final output, reflected in skull motion differed significantly ($p < 0.01$) in the two postures. The monkey undershot the 30° target motion in the quadrupedal position and overshot in upright

where the motions required less effort. An equivalent difference appeared in the head pitch velocity measurements listed in Table 1, which were

1.46 rad/sec in upright vs. 1.24 rad/sec in the quadrupedal position (target velocity gain was 1.57 rad/sec). Comparison of successive excu-

Table 1 Mean (\pm S.D.) of EMG and head velocity response gain, phase, and coherence with respect to position of the visual target in both body positions

	UPRIGHT ^a			QUADRUPEDAL ^a		
	Gain ^b	Phase	Coherence	Gain ^b	Phase	Coherence
BC	0.45 \pm 0.16	112 \pm 18 $^\circ$	0.88	6.77 \pm 1.70	38 \pm 5 $^\circ$	0.97
COM	1.42 \pm 0.35	103 \pm 24 $^\circ$	0.85	9.52 \pm 2.77	38 \pm 5 $^\circ$	0.96
LSA	0.24 \pm 0.10	149 \pm 11 $^\circ$	0.91	1.20 \pm 0.21	35 \pm 9 $^\circ$	0.92
OCI	0.11 \pm 0.04	105 \pm 20 $^\circ$	0.91	1.39 \pm 0.37	34 \pm 4 $^\circ$	0.99
RCmaj	0.70 \pm 0.28	32 \pm 19 $^\circ$	0.87	0.85 \pm 0.40	45 \pm 11 $^\circ$	0.88
RCmin	0.11 \pm 0.04	97 \pm 54 $^\circ$	0.91	3.75 \pm 2.30	32 \pm 3 $^\circ$	0.95
RhCap	5.10 \pm 1.76	138 \pm 19 $^\circ$	0.92	16.42 \pm 1.71	40 \pm 5 $^\circ$	0.98
SCM	0.11 \pm 0.04	29 \pm 90 $^\circ$	0.80	1.87 \pm 2.76	18 \pm 20 $^\circ$	0.91
SPL	0.47 \pm 0.15	133 \pm 12 $^\circ$	0.97	1.45 \pm 0.30	42 \pm 11 $^\circ$	0.88
SSC	10.17 \pm 3.01	153 \pm 11 $^\circ$	0.98	9.53 \pm 2.00	47 \pm 8 $^\circ$	0.95
Head Pitch	1.46 \pm 0.10	90 \pm 3 $^\circ$	1.00	1.24 \pm 0.08	93 \pm 3 $^\circ$	0.99
Head Roll	0.23 \pm 0.15	-6 \pm 66 $^\circ$	0.57	0.40 \pm 0.15	-45 \pm 51 $^\circ$	0.84
Head Yaw	0.12 \pm 0.10	-22 \pm 96 $^\circ$	0.51	0.14 \pm 0.13	-1 \pm 104 $^\circ$	0.56

^a All EMG gain and phase responses, except SSC response gain, are significantly different across body position at the $p < 0.001$ level.

^b Muscle gains are expressed as a percentage of the activation recorded during voluntary head shaking. Head and target gains are expressed as movement velocity/target position. Hence the "ideal" gain is $2\pi f$ or $\pi/2$ for this 0.25 Hz motion. (BC=biventer cervicis ; COM=complexus ; LSA=levator scapular anterior ; OCI=obliquus capitis inferior ; RCmaj=rectus capitis posterior major ; RCmin=rectus capitis posterior minor ; RhCap = rhomboideus capitis ; SCM=sternocleidomastoid ; SPL=splenius capitis ; SSC=semispinalis cervicis.)

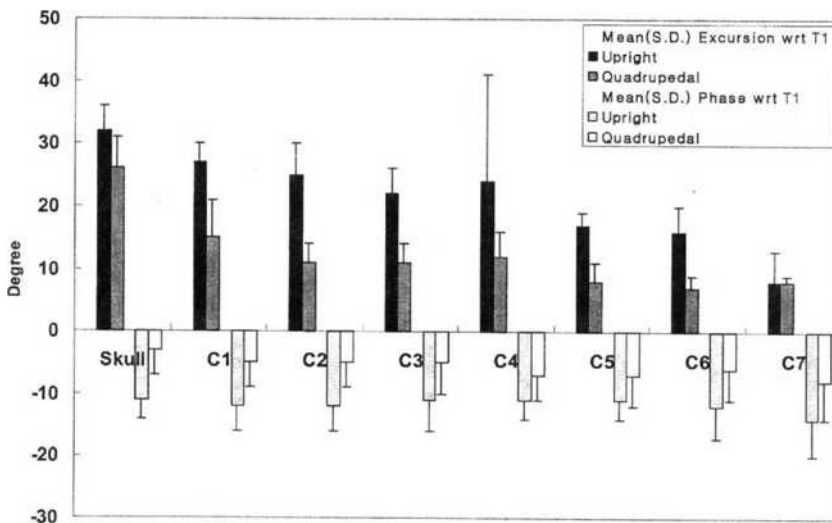


Fig. 1 Mean (S.D.) vertebral angular excursion wrt (with respect to) T₁ and mean phase wrt position of the visual target. Significant differences between body positions at the $p < 0.01$ level for the mean excursions of all of the vertebrae except C₇ and mean phases for skull, C₁, C₂. Significant differences between body positions at the $p < 0.05$ level for mean phase of C₃

sions indicates that the motions were clearly segmented with most of the pitch motion occurring about the four joints in each posture noted in prior studies (Graf et al. 1995; Keshner et al. 1997; Vidal et al. 1986). In upright posture, motions ranging from 5°–8° occurred about C1-skull, C4-C5, C6-C7 and C7-T1. Three of the principal motion centers identified in upright (C1-skull, C4-C5, C7-T1) were also among the

centers about which motions of 4°–8° occurred in the quadrupedal position. However, there was no significant motion about C6-C7 in the quadrupedal position whereas a 4° motion was observed about C1-C2, which moved only 2° in upright. Thus while the kinematics of movement were similar in the two postures, there were notable differences.

The net head movement produced by the head

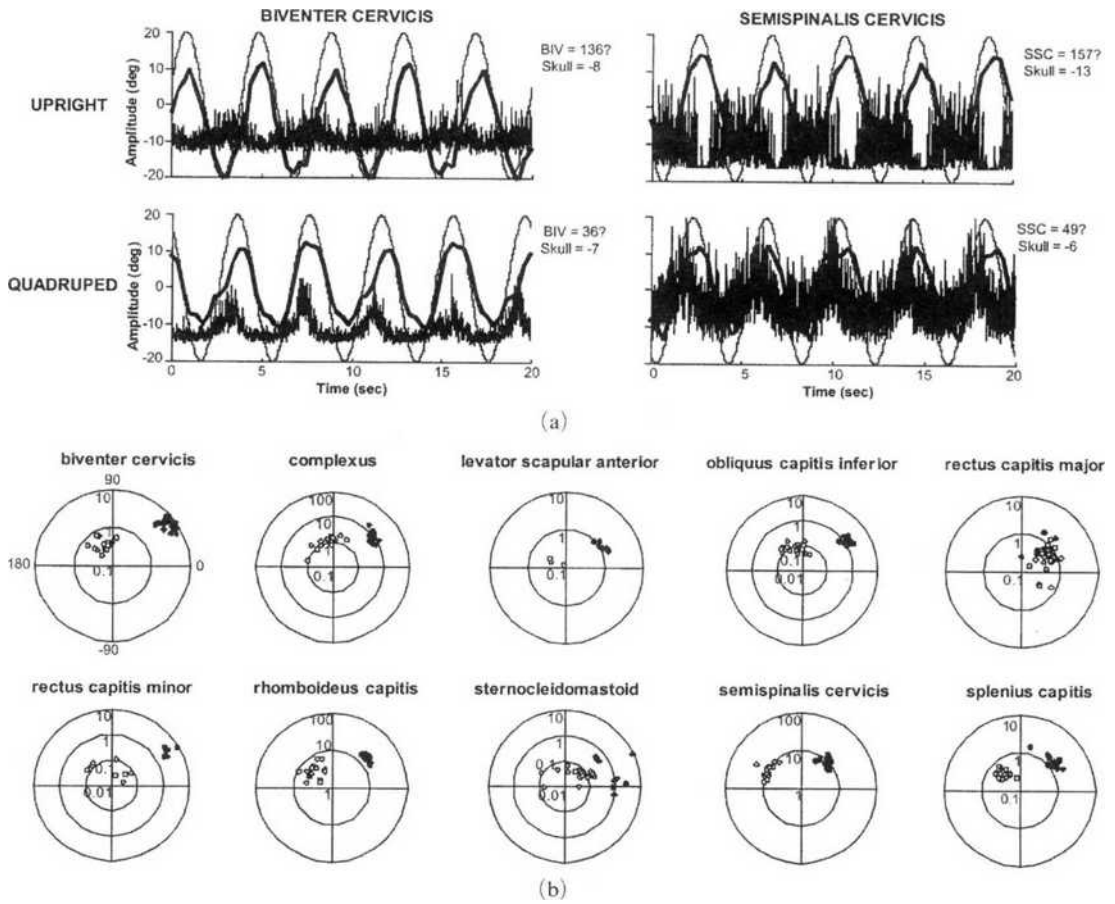


Fig. 2 A. EMG responses of a skull extensor (BIV) and a vertebral extensor (SSC), the visual target (thin line) and the Skull (bold line) in both the upright (top) and quadrupedal (bottom) position. Response phases with respect to the target are printed on each graph. The y-axis represents the excursion of the target ($\pm 20^\circ$) and Skull. EMG response amplitudes are normalized to the head shaking response and plotted as arbitrary units. B. Polar plots showing the relative response gains of muscle EMG for upright (unfilled circles) and quadrupedal (filled circles) trials. The muscle's response is plotted according to its amplitude on a logarithmic scale incrementing outward from the origin. The value of each concentric circle is labeled. Response phases are plotted as a polar angle representing the phase shift between muscle and target. Phase conventions are relative to the peak up position of the target (0°); $+90^\circ$ leads peak up position; -90° lags peak up position; 180° is peak down position of the target

and vertebral motion in both positions closely resembled the sinusoidal shape of the target motion (Fig. 2A). Movement timing, reflected in the phase of the motions with respect to T_1 was quite accurate in both postures. There was, however, a significant ($p < 0.05$) tendency for motion to lag the target more in the upright posture (Fig. 1). This was also seen in head velocities, which were in phase with target velocity when upright but led target velocity by 3° in the quadrupedal position. The unity coherence between target and head velocity indicated that the monkey was accurately matching the velocity of the target in the sagittal plane in both body positions. In the roll and yaw planes, gain response were low and phases had larger variability, but a coherence of 0.84 in the roll plane in the quadrupedal position suggests a component of out of plane motion when head tracking in this body position.

3.2 Muscle activation patterns

In contrast to the relatively subtle differences in movement kinematics, there were large differences in muscle activation patterns in the two postures. Coherence between muscle response phases and target position fell between 0.88 and 0.99 (Table 1) indicating that a linear dynamic relation existed between the stimulus and the muscle activation behavior. One clear difference between postures was the markedly stronger muscle activation in the quadrupedal position. Except for SSC and RCmaj, EMG gains were significantly greater when the animal was standing in the quadrupedal position than when seated upright ($p < 0.001$), and this was seen consistently across trials (Fig. 2B). There were also differences in muscle utilization. Compared to the large activation accompanying a head shake, only two muscles were well activated in upright - Rhcp at 5.1% and SSC at 10.2%. These two muscles were also strongly activated in the quadrupedal position as well as two other muscles - BC at 6.8% and Complexus at 9.5%. Activation of the rotator and flexor muscles OCI and SCM was very weak in the upright posture and significantly stronger in the quadrupedal position.

Response phases were also strongly posture dependent. In the quadrupedal position, all of the muscles exhibited less than a 45° lead relative to peak upward position of the head. SCM, a flexor muscle, had the smallest phase lead. In the upright position, the relationship between peak muscle activation and target motion was more variable. The majority of the muscles were activated as the head moved from the peak downward position toward its peak upward velocity (Table 1). Muscles attached to the skull (BIV, COM, OCI, RCmed) responded nearest to peak upward velocity of the head. Vertebral extensors (Rhcp, SSC, SPL, LSA) lagged peak downward position. Only RCmaj, a short skull extensor, and SCM, a flexor, had phases falling between peak upward head velocity and position (Fig. 2B).

4. Discussion

We examined simultaneous muscle activation and vertebral motion in a rhesus monkey in two body postures to clarify the effects of changing anatomical constraints during voluntary head tracking. Body posture was a significant variable in determining both the range of cervical joint motion and the amplitude and directional propensity of neck muscle activation patterns. Larger response gains and concurrent phases of the muscles in the quadrupedal position would suggest that gravity acting on the horizontally oriented spinal column required greater activation and a collective response of the muscles. This produced less motion between joints as though the vertebral column was being locked for stability. Head tracking was attained primarily by motion at skull- C_1 . The outcome of decreased joint motion was more accurate head tracking in the quadrupedal position than when seated upright. In upright, muscles were activated in functional groupings defined by their anatomical arrangement. Motion of several joints within the cervical column contributed to the task.

Previous literature suggests that, because of their complex relationships relative to the underlying joints, neck muscles can change their function (Keshner, 1994; Richmond et al., 1992;

Wickland et al., 1991). This muscle variability was dependent upon the task being studied (Dunbar et al., 1986; Keshner et al., 1992; Macpherson et al., 1989). Our functional muscle groups were divided into those that flex or extend the skull, biventer cervicis, complexus, obliquus capitis inferior, rectus capitis medius, sternocleidomastoid, and those that extend the vertebrae, rhomboideus capitis, semispinalis cervicis, splenius capitis, levator scapula anterior. Rectus capitis major, a short, suboccipital muscle that performs solely in the pitch plane for head extension (Richmond et al., 1991) moved the head about the upper cervical joint regardless of body posture. This would be expected of a muscle with a large moment arm about the skull-C1 joint (Keshner et al., 1997). A posture dependent dissociation between the short suboccipital and the long intervertebral muscles may suggest that different central mechanisms selectively recruit the muscles during functional activities (Richmond et al., 1992).

Our data support the data of Thomson et al. (1994) who rotated the head of a prone cat with the cervical column oriented perpendicular or parallel to gravity. They divided their muscle groupings into variant (superficial muscles with skull attachments) and invariant (lateral and caudal muscles with intervertebral or scapular attachments) synergies. There are numerous data to indicate that patterns of motion of the vertebral column (de Waele et al., 1989; Graf et al., 1995; Vidal et al., 1986) and muscle synergies for specific tasks (Dunbar et al., 1986; Macpherson et al., 1989) are consistent across species. Our results suggest that relevant parameters controlling task dependent muscle activation patterns include the posture adopted by the animal prior to the movement (i.e., the angles of various linked segments with respect to gravity and to the desired target) and the degree to which the joints are free to move.

Acknowledgment

These experiments were performed with the technical assistance of Mr. Larry Martin and Ms.

Rosalynn Torralba. We thank Drs. Francis Richmond and Gerry Loeb for their expert assistance with the surgical procedures.

References

- Berthoz, A., Graf, W. and Vidal, P. P., 1991, *The Head-Neck Sensory-Motor System*, Oxford University Press, New York, pp. 101~103.
- De Waele, C., Graf, W., Josset, P. and Vidal, P. P., 1989, "A radiological Analysis of the Postural Syndromes Following Hemilabyrinthectomy and Selective Canal and Otolith Lesions in the Guinea Pig," *Experimental Brain Research*, Vol. 77, pp. 166~182.
- Dunbar, D. C., Horak, F. B., Macpherson, J. M. and Rushmer, D. S., 1986, "Neural Control of Quadrupedal and Bipedal Stance: Implications for the Evolution of Erect Posture," *American Journal of Physiological Anthropology*, Vol. 69, pp. 93~105.
- Graf, W., De Waele, C. and Vidal, P. P., 1995, "Functional Anatomy of the Head-Neck Motor System of Quadrupedal and Bipedal Mammals," *Journal of Anatomy*, Vol. 186, pp. 55~74.
- Keshner, E. A., Campbell, D., Katz, R. and Peterson, B. W., 1989, "Neck Muscle Activation Patterns in Humans During Isometric head Stabilization," *Experimental Brain Research*, Vol. 75, pp. 335~344.
- Keshner, E. A., Baker, J. F., Banovetz, J. and Peterson, B. W., 1992, "Patterns of Neck Muscle Activation in Cats During Reflex and Voluntary head Movements," *Experimental Brain Research*, Vol. 88, pp. 361~374.
- Keshner, E. A., 1994, "Vertebral Orientations and Muscle Activation Patterns During Controlled head Movements in Cats," *Experimental Brain Research*, Vol. 98, pp. 546~550.
- Keshner, E. A., Statler, K. D. and Delp, S. L., 1997, "Kinematics of the Freely Moving head and Neck in the Alert Cat," *Experimental Brain Research*, Vol. 115, pp. 257~266.
- Macpherson, J. M., Horak, F. B., Dunbar, D. C. and Dow, R. S., 1989, "Stance Dependence of Automatic Postural Adjustments in Humans," *Experimental Brain Research*, Vol. 78, pp. 557~

566.

Richmond, F. J. R., Thomson, D. B. and Loeb, G. E., 1992, "Electromyographic Studies of Neck Muscles in the Intact Cat. I. Patterns of Recruitment Underlying Posture and Movement During Natural Behaviors," *Experimental Brain Research*, Vol. 88, pp. 41~58.

Runciman, R. J., Richmond, F. J. R., 1997, "Shoulder and Forelimb Orientations and Loading in Sitting Cats: Implications for head and Shoulder Movement," *Journal of Biomechanics*, Vol. 30, pp. 911~919.

Thomson, D. B., Loeb, G. E. and Richmond, F.

J. R., 1994, "Effect of Neck Posture on the Activation of Feline Neck Muscles During Voluntary head Turns," *Journal of Neurophysiology*, Vol. 72, pp. 2004~2014.

Vidal, P. P., Graf, W. and Berthoz, A., 1986, "The Orientation of the Cervical Vertebral Column in Unrestrained Awake Animals. I. Resting Position," *Experimental Brain Research*, Vol. 61, pp. 549~559.

Wickland, C. R., Baker, J. F. and Peterson, B. W., 1991, "Torque Vectors of Neck Muscles in the Cat," *Experimental Brain Research*, Vol. 84, pp. 649~659.