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A novel system to measure head and trunk posture during daily activities

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Abstract: Although the posture and jaw function has been speculated to relate to each other, little scientific evidence is presented in humans due to lack of recording method. To clarify that, we designed and tested a standard noninvasive, accurate, and repeatable clinical method to record head and trunk posture for hours in freely behaving humans. The system was evaluated by measuring the following tasks successively conducted by five subjects: 1) reading a sheet of text (vertical and horizontal documents) while sitting on a chair, 2) sitting on a chair (in an upright position and freely), 3) walking slowly (in an upright position and freely) in a room, 4) tilting the head (anterior and posterior directions and right and left directions) and 5) turning the head (right and left) while sitting on a chair. Characteristic features were observed in the volunteers performing the reading and head movement tasks. While reading text of vertically lined letters, head movement was in the antero-posterior direction along with the direction of the letters, however, movement was limited when the volunteers read text of horizontally lined letters. During head tilting and turning, head and trunk movement was in the same direction for pitch but in the opposite direction for roll. In conclusion, this system accurately records head and trunk posture individually in human subjects; it is easily operated for clinical use and small enough to sit on the patient's trunk for hours of recording. A potential problem may be its battery consumption; however, current technology may overcome this.

I. Introduction

Dental clinicians often seek to understand relationships between head posture and jaw function. Temporomandibular disorder, for example, is accompanied by head, neck, and shoulder muscle symptoms.¹⁻³⁾ Since occlusal treatments are often effective for these patients,⁴⁻⁶⁾ the stomatognathic system appears to be related to the head-neck motor system. Evaluation of head-jaw relationships in humans⁷⁻¹³⁾ and in animals¹⁴⁻¹⁶⁾ has revealed synchronization of head movement with rhythmic jaw movements.

Head movements occur together with the mandible during mouth opening-closing tasks in humans,^{7,8,10,11)} and electromyographic activities in human neck muscles are enhanced during jaw clenching and grinding.^{7,17)} Several lines of neurophysiological evidence suggested the existence of close connections between trigeminal and cervical neuromuscular systems.¹⁸⁻²⁰⁾ However, it is not clear whether rhythmic head motion occurs concomitantly with natural jaw movements associated with mastication, swallowing and phonation. Thus, methods to record trunk and head movements during physiological behaviors have long been sought.

To understand the neural control mechanism underlying head movement, Igarashi et al.¹⁴⁾ studied the relationship between the head-neck and jaw motor systems during natural chewing and cortically induced rhythmic jaw movements in rabbits; head movement and neck muscle activity synchronized rhythmically with jaw movements during natural mastication. Thus, neck muscles might contribute to rhythmic head movement after loading the tooth with food. Zeredo et al.^{15, 16)} applied natural pressure stimulation to the upper first molars of rats while motor unit electromyographic activity was recorded from the dorsal neck splenius muscle. They concluded that periodontal inputs may play an important role in controlling the motor activity of neck muscles, in addition to its well-known coordination of the masticatory function.

On the other hand, the assessment of head and cervical range of motion (ROM) is an important part of the clinical evaluation of patients reporting several disturbances. Indeed, head and neck motion often accompanies the movements of other body districts, such as mouth opening and closing.^{7, 8, 10, 11)} Alterations in head and neck movements have been reported not only in subjects with spine pathologies,^{21, 22)} but also in patients with temporomandibular disorders.^{23, 24)} However, from an assessment of published reliable studies for

cervical spine range-of-motion measurement tools, Jordan²⁵⁾ reported that measurement tools have not been fully tested for reliability. Thereafter, a standard noninvasive, accurate and repeatable clinical method to measure head and trunk posture is greatly needed.

In this study we developed a recording system to measure head and trunk postures for hours in freely behaving humans.

II. System design

The recently developed micromachine technology has enabled the manufacture of a small accelerometer. The surface micromachined sensor element is made by depositing polysilicon on a sacrificial oxide layer that is then etched away to leave the suspended sensor element. The actual sensor has multiple cells, each with a differential capacitor sensor for sensing structure. The differential capacitor sensor is composed of fixed and moving plates attached to a beam that moves in response to acceleration. Acceleration due to movement and/or the earth's gravity is recorded, i.e., the accelerometer can respond to the inertial gravity as well as the static gravity field. The degree of beam movement is then converted into an electrical signal with the differential capacitor sensors placed in each cell unit. The ability to measure the earth's gravity may facilitate tilt measurement. Pitch and roll at desired points of the trunk could be measured for hours with multiple sensors in freely behaving humans.

We have thus applied sensors to measure posture in humans. Since two tilt sensors are on one chip, pitch and roll can be measured with one chip of an integrated circuit. For this purpose, a one-chip integrated circuit (ADXL-250, ANALOG DEVICES) was employed, in which two pre-calibrated accelerometers were assembled in a small body (7 x 10 x 5 mm, 5-gr). One sensor element detected postural changes in the sagittal (anterior and posterior (A-P) direction) and frontal (right and left (R-L) direction) planes. The sensor elements were placed centrally on glasses and just above the center of the scapulae. The former detected changes in head tilts and the latter detected trunk tilt changes in two planes (Fig. 1).

The system was designed to separate the two components picked up by the accelerometer, i.e., inertial gravity field and static earth's gravity. We sought to differentiate the components in electrical circuits and introduced analog filters into the system. The actual test indicated that the low-pass filter at 1 Hz adequately differentiated signals related to

Fig. 1 Schematic representation of sensor setting (A) and recording image (B) of the system.

Sensor elements, which detect postural changes in the saggital (sensors a and c) and frontal (sensors b and d) planes, may be placed centrally on glasses and just above the center of the scapulae. After the signal processing, outputs from the sensors can be reconstructed to represent the head movements in time sequence and in the horizontal plane as two-dimensional movement orbits.

postural changes and not to transient movements. Changes in head and trunk postures (i.e., tilt and drift, respectively) were traced electrically in time sequence, as the inclination angle (IA) against the axis oriented to the earth's gravity (i.e., the vertical axis). The tilt of the head and trunk toward the anterior and right directions was denoted as plus (+) and toward the posterior and left directions as minus (-).

Fig. 2 shows details of the system composed of accelerometers, amplifiers with a low-pass filter, differential amplifiers, a microprocessor based data acquisition board with a memory card, and a personal computer. To measure head movement against the trunk, differential amplifiers for sensor output from the head and trunk were used.

A total of four channels of electrical signals (i.e., those of pitch and roll corresponding to head tilt and trunk drift, respectively) were fed into a microprocessor through a 12-bit A/D converter equipped on the data acquisition board and recorded on a memory card in text format. The memory card held at least 64 mega-bites of data and could transfer data to personal computers. After data transferal to a personal computer, data were converted into IAs, displayed on the computer screen, and stored on a hard disk for further analysis

with customized software. The IAs for pitch and roll were displayed on the screen as IAs in the A-P and R-L directions, respectively.

III. System evaluation

1. Subjects

Five subjects were randomly selected. The aim and methods of the experiment were thoroughly explained to the subjects before any of the following procedures were carried out. Informed consent was obtained from each subject after the explanation. Three dentists, who did not participate in the system development, evaluated the system.

2. Procedures

Each subject was asked to wear the glasses and suspender with the sensor elements (mentioned above). The head position was defined as null for the sensors on the glasses (i.e., sensors for the head posture) when the Frankfurt plane was perpendicular to the gravitational axis: i.e., the plane was parallel to the horizontal plane. The trunk position was defined as null when the subject sat on a chair comfortably in an upright position. No special holders were set on the chair

Fig. 2 Block diagram of the recording system.

The system includes two sensor units (four accelerometers), low pass filters ($f_c = 1$ Hz), differential amplifiers, and buffer amplifiers in analog division, a microprocessor based data acquisition unit, and a memory card. The memory card can hold data obtained from hours of recording and can transfer the data into any personal computer. The final data can be processed on a personal computer. System initiation or starting the system, monitoring system performance on the screen, and setting parameters of the recording system can be done with a personal computer through a RS-232C line.

to fix the head or trunk movement.

The subjects successively conducted the following tasks: 1) reading a sheet of text silently (vertically and horizontally lined documents) during sitting on a chair, 2) sitting in a chair (in an upright position and freely) for a while, 3) walking slowly (in an upright position and freely) in a room, 4) tilting the head (anterior and posterior directions, and right and left directions) and 5) turning the head (right and left) while sitting on a chair. For measurement during tasks 1), 4) and 5), each subject was instructed to sit on a chair comfortably in an upright position.

IV. Results

1. Operation

Three operators tested the system. The operators had no previous experience in engineering field; however, an hour of instruction was sufficient to familiarize them with the operation. The operation consisted of 1) system preparation (connect the recording system to a personal computer with a RS-232C cable, start the system, monitor system performance on the screen, and set parameters on the recording system through the personal computer, such as sampling speed and durations), 2) sensor setting on the head and shoulder, and 3)

start recordings. Sensor setting could be accomplished within 5 minutes. After completion of the recordings, operators stopped the system power and removed the PC card (memory card) from the system. Once the data on the PC card were downloaded to a personal computer, the data could be handled with many kinds of application software, such as Excel, so that the changes in postures could be displayed in time sequence and/or moving trajectories along the horizontal plane. The maximum recording duration was 2 hour limited by battery consumption. No one complained about the system operation, except the high level of battery consumption.

2. Clinical application

Fig. 3 shows sample recording in time sequence while a subject performing the five tasks (i.e., reading texts, sitting on a chair, walking, tilting head, and turning head) successively. Upper traces and lower traces represent head tilt and trunk drift in either pitch or roll (i.e., antero-posterior direction (thin line) and right-left direction (thick line)), respectively. At the beginning of each recording, output from the accelerometers was set at null for the trunk when the subject was instructed to sit upright on a chair and for the head when the Frankfurt plane was parallel to the horizontal plane, respectively.

Fig. 3 An example of recording represented in time sequence.

Upper traces and lower traces represent head tilt and trunk drift in either pitch or roll (i.e., antero-posterior direction and right-left direction), respectively. The null position of the head was set when the Frankfurt plane was parallel to the horizontal plane. Recordings were made during reading, sitting, walking, head tilting and head turning task performance. Thin and thick lines exhibit pitch and roll, respectively, in either head or trunk movement. Characteristic features were observed in the volunteers while they performed the reading and head movement tasks. While reading text of vertically lined letters, the head moved in the antero-posterior direction as if tracing the letters. However, head movement was limited when the volunteers read text of horizontally lined letters. During head tilting and turning, the head and trunk showed cooperative movements in the same direction for pitch but in the opposite direction for roll.

In general, the null position, especially in the right-left direction, was relatively consistent for both the head and trunk. In fact, the head and trunk moved from the null position during reading; however, when the subject was asked to sit upright, the trunk and head returned to the original position (i.e., null position).

Interestingly, the trunk and head moved in parallel in the antero-posterior direction and in opposite ways in the right-left direction, consistently during all the tasks tested.

Sitting task

While sitting in an upright position, the trunk and head were stabilized to a small extent at the null position. However, when the subject sat freely on a chair, the head tilted a little from the null position.

Text reading task

Two types of text (vertically and horizontally lined) were read by each subject. Reading the two kinds of text (silent reading) resulted in characteristic head movements. While the subject read a text of vertically lined Japanese letters, the head shifted forward about 15 degrees gradually in the antero-posterior direction with cyclic up and down movements.

However, the head remained in the original, stable position while the subject read the horizontal text in either direction; in the antero-posterior direction the head was about 20 degrees in the anterior position, which succeeded the former behavior, while in the right-left direction, the head tilted slightly (about 5 degrees) to the left at the beginning of the task.

Projection on the horizontal plane demonstrates the entire head movement sequence during the text-reading task (Fig. 4A). The trunk moved towards the anterior and right directions during the early part of task performance, where it remained until the end of the task.

Walking task

While walking, the trunk moved to a greater extent than the head, but not as much as during head tilting and head turning. When the subject was instructed to walk in an elected posture, the head and trunk stabilized to a smaller extent than while walking freely.

Head turning task

During head turning to the right and left, a plateau was recorded at the anterior area. Otherwise, the two traces in time sequence were cyclical with a 90-degree time shift,

Fig. 4 Movement trajectories of the head during the reading task (A) and during the head turning task (B) represented on the horizontal plane.

In A, head movements while reading vertically lined text (dotted lines) and horizontally lined text (solid line) are reconstructed on the horizontal plane. In B, head movements during the head turning task are reconstructed with trunk movements (enclosed by a small square). The projections clearly show the characteristics of each movement. Specifically, head turning movements coordinated well with the head movement trajectory during either right or left turning, and the trunk moved in the reverse direction with smaller amplitude. The same datum are also shown in Fig. 3 in time sequence.

which is well represented on the two-dimensional trace in the horizontal plane; i.e., the movement trajectory shows a rather flat overall shape without a front fragment (Fig. 4B, thick lines). The right and left movement trajectories were well coordinated.

The trunk moved in parallel with the head in the antero-posterior direction but in the opposite direction of the head in the right-left direction. The amplitude of trunk movement was, however, smaller in both directions. The movement trajectory in the frontal plane shows this clearly (Fig. 4B in a square).

V. Discussion

1. System design

Alterations in the range of motion (ROM) of the head and cervical spine have been reported in patients with neck²⁾ and shoulder pathologies,³⁾ temporomandibular joint and masticatory muscle disturbances,²⁶⁾ headache,¹⁾ and ocular mobility²⁷⁾ changes. Many kinds of recording systems have been developed to measure ROM (see Jordan²⁵⁾ for review).

Noninvasive cervical movement recording systems are available in the market. One of the most sophisticated systems analyzes motion three-dimensionally by measuring

the propagation time of ultrasound pulses.²⁹⁾ The ultrasonic system measures movements with intrinsic measuring uncertainty of approximately 1-degree, but the subject must wear a head cap and shoulder pad and stay in a small area (about 1 m from the ultrasound source). Moreover, the head cap and shoulder pad are wired to the main system. The ultrasonic system is superior to our system for measurement of cervical rotation, which cannot be measured by our system. However, our system may offer superior resolution, marker size and mobility at a lower cost. The resolution of our system is as high as 0.54-degree, and the sensor unit is so small to be unobtrusive.

Opto-electronic system has also been used to record head and trunk movements.²⁹⁾ The system used wireless, stroboscopically illuminated retro-reflective markers, and high-resolution infrared sensitive charge coupled device cameras with electronic shutters. The marker positions were detected by a real-time video processor, and a software calculated the three-dimensional coordinates of their centers of gravity. Although the opto-electronic system made the subject free from heavy instruments, the recording was limited in a small area as such the position when the subject sat in

an upright chair. The error of the method was reported to be 1.5-degree for head flexion, extension and rotation, and 2.9 or 0.8-degree for head lateral bending (left side or right side).

Again the opto-electronic system is superior to our system for measurement of cervical rotation; however, our system can record the postural change in time sequence with a handy device available anytime and anywhere with high resolution. Since the resolution of our system is secured by the sensor, it is independent of the operation; i.e., easy but repeatable measurement can be accomplished by anyone. The advantages of the new recording system may overcome the lack of cervical rotation recording.

2. Clinical point of view

Keshner²⁹⁾ evaluated the relative contribution of inputs from the vestibular system and the trunk to head-trunk coordination and concluded that the vestibular system might dampen later response components and monitor the position of the head in space secondary to feedback from segmental proprioceptors rather than generate postural reactions. In this study, he used accelerometers to record the head-neck relation. However, his system was reported to be 485-gr, and might influence the measurement. In this respect, our system is about 10-gr and may be useful for this kind of research. In fact, our system could clearly display the relations between head and body postures, in that the trunk moves in parallel with the head in the antero-posterior direction but in the opposite direction of the head in the right-left directions.

The assessments of ROM and of pain after ROM test are reportedly among the best estimators of cervical and temporomandibular disability.²⁶⁾ In this respect, functional coupling between jaw and head movements in humans has been extensively studied mainly at three laboratories by different recording systems.⁷⁻¹³⁾ After concomitant recording of the jaw, head, and trunk, Yamabe et al.⁹⁾ showed trunk and head fluctuations during jaw tapping, indicating that functional linkages occurred not only between the jaw and head but also between the head and trunk. Thus, fluctuations of the trunk are mandatory during coordinated mandible and head movements. In this respect, the newly developed posture recording system may be concluded to contribute as a clinical device for physiological examination.

The quantitative study of head and cervical spine movements is more complex than the examination of limb joint mobility because of concomitant movements of other

body districts, first of all the upper dorsal spine and shoulder girdle. Therefore, in clinical examinations with conventional recording system these 'external' movements were requested to be reduced to a minimum or, at best, eliminated by fixing the body district. Obviously, this kind of data cannot be directly applied to everyday life, but they only can be usefully employed for a numerical definition of normal ranges, and for clinical applications. Our system can easily differentiate the head and body districts in their movements. The system also records the head and body postures in time sequence with a time resolution of second-order.

This study shows a recording in which posture is clearly represented. Furthermore, the recording chart portrays more than posture, i.e., head and trunk movements can trace subject behavior. Thus, we expect that this system can be used to record daily behavior along with EMG, etc. In conclusion, the system can accurately record head and trunk posture individually in humans; the system can be used easily in the clinic and is small enough to sit on a patient's trunk for hours of recording. The level of battery consumption is high, but this problem can probably be easily overcome.

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