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Three-Dimensional Kinematic Analysis of Active Cervical Spine Motion by Using a Multifaceted Marker Device

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Abstract— **Assessing cervical range of motion (CROM) is an important part of the clinical evaluation of patients with conditions such as whiplash syndrome. This study aimed to develop a convenient and accurate system involving multifaceted marker device (MMD)-based assessment of 3-dimensional (3D) dynamic coupled CROM and joint angular velocity. We used an infrared optical tracking system and our newly developed MMD that solved problems such as marker shielding and reflection angle associated with the optical tracking devices and enabled sequential and accurate analysis of the 3D dynamic movement of the polyaxial joint and other structurally complicated joints. The study included 30 asymptomatic young male volunteers (age, 22–27 years). The MMD consisted of 5 surfaces and 5 markers and was attached to the participant's forehead. We measured active CROM (axial rotation, flexion/extension, and lateral bending) and joint angular velocity by the MMD. The MMD was easy to use, safe for patients and operators, could be constructed economically, and generated accurate data such as dynamic coupled CROM and angular velocity.**

I. Introduction

The assessment of neck kinematics is one of the most important aspects of clinical evaluation in orthopedic and rehabilitation services for assessing many conditions such as traumas, head and neck problems, shoulder muscle tenderness, inflammatory conditions, rheumatic disorders, and dental dysfunction [1-3]. The most studied neck trauma is whiplash syndrome, which typically results from motor vehicle accidents [1, 4-6].

Cervical range of motion (CROM) impairment is the impairment observed most frequently in the clinical setting [5]. Various methods are available for evaluating CROM, including radiographs [7], goniometers [8], and inclinometers, as well as more advanced technologies such as ultrasonic systems [9] and optoelectronic systems [3]. Although goniometers, inclinometers, and radiographs are generally used in clinical practice, these devices are limited to 2-dimensional investigation under static conditions.

Kinematic variables associated with movement can provide more information pertaining to motor control disturbances [4]. Although many studies have reported measurements using a 3-dimensional (3D) system, most of them focus only on primary movements [9,10]. However, coupled joint motions also play an important role in cervical motion [3,11-13]. These coupled motions may be affected by cervical disorders; therefore, studying them should very likely facilitate diagnosis or aid in evaluating therapeutic efficiency [2,14].

We think that our newly developed multifaceted marker device (MMD) would enable highly accurate measurement of dynamic coupled CROM of basic movements of the cervical spine in addition to static CROM. In general, optical tracking systems are accurate and have no danger to the human body like radiation and little effects on peripheral medical equipments, but have problems of marker reflection angle and shielding which prevented us from measuring wide angle motions. The MMD solved these problems and enabled accurate evaluation of 3D wide angle movements by utilizing the advantage of an optical tracking system. We succeeded in measuring surgeons' head pose by using our newly developed optical tracking system, which included the MMD [15]. The system measures complicated 3D dynamic movements, including rotation.

The aim of this study was to develop an optical tracking system using the MMD-based assessment of 3D dynamic CROM and joint angular velocity.

II. Materials and Methods

A. Subjects

Thirty asymptomatic volunteers were recruited from the Kyoto Prefectural University of Medicine staff and student body. All the subjects were men aged 22–27 years (mean age = 23.9 ± 1.31 years). The exclusion criteria were no history or pathological features of neck trauma, no known neuromuscular pathology, and no history of spinal disorders. We obtained institutional approval of protocol and informed consent, and provided subjects with a detailed explanation of the procedures and risks.

B. Instrumentation

We used an infrared optical tracking system (Polaris, Northern Digital Inc., Waterloo, Ontario, Canada) to measure 3D dynamic cervical motion (sampling rate, 60 Hz) and the MMD that we developed. The tracking area of a single marker is limited, making it useful for analyzing simple fine motion but not 3D wide-angle motions involving flexion and rotation. We constructed the MMD (Fig.1) comprising 5 markers and 5 surfaces (1 square surface and 4 trapezoidal

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surfaces) to solve the associated problems of reflection angle and marker shielding. The square surface was placed at the center of the MMD, facing the position sensor, and the 4 trapezoidal surfaces were placed to each side of the device. Seamless switching of markers from different angles enabled measurement of wide-angle motion without losing information (Fig.2). We integrated data from all markers into a single frontal marker, which allowed this MMD to record data as a sequence of actions. This device could measure 215° rotation and flexion/extension and 360° lateral bending (left and right side) of the cervix. We used a Let's note CF-W5 laptop computer (Panasonic, Kadoma, Japan) to analyze data.

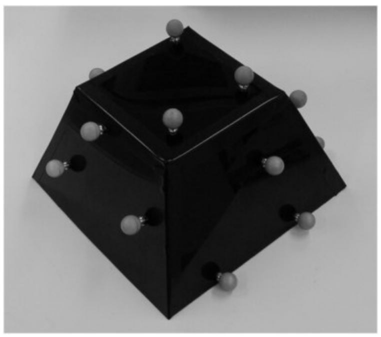

Figure 1. The MMD comprising 5 markers and 5 surfaces, capable of measuring 215° rotation and flexion/extension and 360° lateral bending of the cervix. This MMD was made of an acrylic board and weighed 120 g.

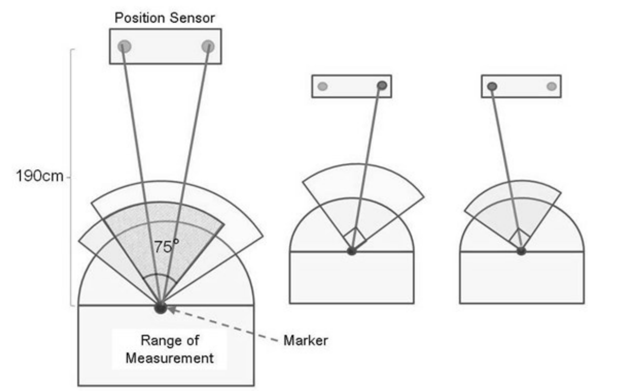

Figure 2. Relationships between reflection angles and marker measurement angles. At the central position 190 cm distance from a position sensor, a 75° angle is required to capture a marker's reflection with both eyes of the sensor. Therefore, an angle of 105° and over must be set to avoid the loss of information at the switching of markers.

C. Procedure

The subjects sat upright in a straight-backed chair with their spine pressed against the back of the chair toward the Polaris position sensor, with feet resting on the ground to reduce thoracic motion (Fig. 3). They performed maximal right and left axial rotation, maximal flexion/extension, and maximal right and left lateral bending 3 times for each motion. All subjects started the movements from a neutral position (looking straight ahead); maximal magnitudes for both sides were reached continuously for 5 seconds. Three measurements were obtained for each movement, with a short break between each measurement. We didn't indicate execution speed to measure CROM. We placed the surgical headgear with the MMD on the subjects' foreheads and the Polaris position sensor on a tripod placed 190 cm in front of them. In addition, we attached a single marker on the chest to measure the motion of the trunk.

Next, we measured maximum angular velocity of axial rotation, flexion/extension, and lateral bending. All subject started the movements from an unrestrained position at a time of their choosing. They were asked to move their head as fast as possible to measure angular velocity. Each subject was assessed 3 times for each movement. All measurements were obtained on the same date.

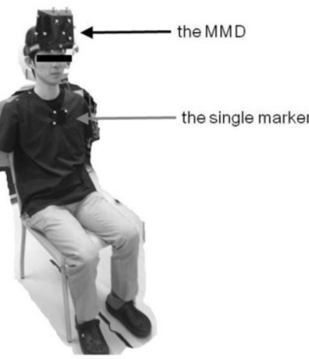

Figure 3. The subject is sitting upright in a straight-backed chair, with feet resting on the ground to reduce thoracic motion. He is wearing a headgear with the MMD on his forehead and a single marker on his chest.

D. Data analysis

We used the CROM data obtained using the MMD to calculate the angular difference between maximum and frontal positions. The MMD could measure slow and fast coupled joint motions. We used all the data obtained using the MMD to prepare a linear plot, which changed depending on the speed and angular frequency of the wave (Fig. 4). Large slow movements generated wide and long amplitude waves, and fine fast movements generated narrow and short waves. The resulting plots were sigmoid in shape. We considered the maximum slope of the sigmoid curve as the maximal instantaneous angular velocity. The maximum value within each plot was determined for each subject and movement. The median value of the 3 trials was calculated. Microsoft Excel 2007 (Microsoft, Redmond, WA, USA) was used to analyze data.

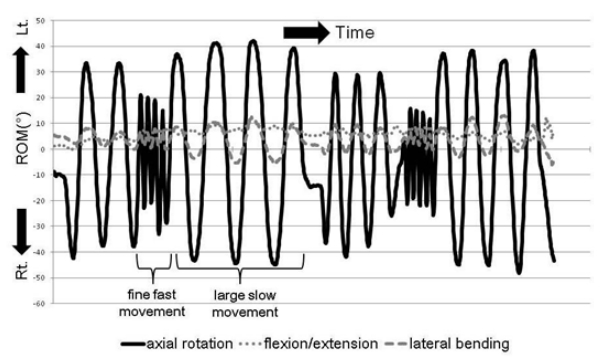

Figure 4. Graph showing MMD data for primary axial rotation with coupled

flexion/extension and lateral bending for 2 minutes under the following conditions: normal movement, fine fast movement, and large slow movement.

III. Results

We could obtain the full cycle CROM data from the MMD assessments. Using the MMD, the average angle of right/left axial rotation was found to be 72.4 ± 7.1°/72.4 ± 5.4°, that of flexion/extension was 51.7 ± 10.5°/66.6 ± 10.7°; and that of right/left lateral bending was 42.8 ± 5.6°/43.9 ± 5.6°.

Table I provides angular velocity and maximal instantaneous angular velocity values.

TABLE I. Median Values of Angular Velocity and Maximal Instantaneous Angular Velocity Measured by the MMD

Parameters	***Angular velocity (degree/second)***	***Maximal instantaneous angular velocity (degree/second)***
Rt. Rotation	605.9 ± 87.0	961.0 ± 169.4
Lt. Rotation	617.8 ± 119.1	968.4 ± 170.4
Flexion	439.1 ± 66.8	688.6 ± 125.5
Extension	441.5 ± 77.5	611.2 ± 83.1
Rt. Lateral Bending	316.0 ± 63.0	499.3 ± 72.0
Lt. Lateral Bending	320.0 ± 62.1	485.9 ± 64.9

IV. Discussion

Here, we describe a new cervical spine motion assessment method involving the MMD, which provides an accurate and convenient method for analyzing 3D kinematic motion of complex joints such as the cervical spine. Compared to most of conventional 3D measurement methods, the MMD could measure not only primary movements but also coupled movements. Quantification of cervical spine motion during continuous activity provides important insights into the disease process in overuse syndromes, joint degeneration, and trauma. Coupled joint motions play an important additional role in cervical motion by comparison with primary motions [3,11,12] and may be affected by cervical disorders.

Various methods are available for evaluating CROM [7,8]. Although goniometers, inclinometers, and radiographs are generally used in clinical practice, these devices are limited to 2-dimensional investigation under static conditions. Dynamic radiographs are used to assess joint motion but involve the issue of exposing the subject to ionizing irradiation. Meanwhile, advanced technologies, which can measure 3D dynamic range of motion, require complex equipment and are very expensive, limiting their use to research settings. In addition to performance, the system must be safe, easy to operate, have a simple design, and provide economical performance. Compared to a low cost motion capture system like Microsoft's Kinect (Microsoft, Redmond, WA, USA) which was conducted a clinical research trial [16], our system has advantage in accuracy. Our system comprising a Polaris and a laptop computer occupies a small space (1 m^2) and has little effect on surrounding medical equipment. Measurements are easy to obtain without registration, and subjects only have to wear the MMD and sit upright in a straight-backed chair. Moreover, a single procedure can be used for determining all CROMs without changing position in small areas. The other advantage is that the measurements acquired by devices for measuring CROM must not be affected by the laboratory technologist's level of skills and must maintain reliable accuracy. Furthermore, the devices can improve accuracy by correcting superfluous motions such as those that occur in the trunk region when measuring CROM.

We considered several other methods for measuring and analyzing 3D kinematics. An optical sensor is sensitive, senses motion remotely, and has little effect on the subjects' performance. Therefore, the optical tracking system is the best system available for noninvasive detection of cervical kinematics. Polaris is easy to use and occupies a relatively small space. The optical tracking system is highly accurate and has little effect on peripheral equipment, thereby making it useful for analyzing simple fine motions. However, the optical tracking system has the issues of reflection angle and marker shielding, which prevent tracking of 3D wide-angle motion involving rotation. We therefore constructed the MMD and solved the associated problems of reflection angle and marker shielding [15]. Our Polaris-based system was easy to use and allowed an accurate 3D study of both primary and coupled movements for all degrees of freedom. This system can help analyze 3D kinematics of joint range of motion, from uniaxial to multiaxial joints, and can be applied to various fields such as rehabilitation or sports medicine.

We determined CROM and angular velocity. The CROM data acquired here using the MMD are in good agreement with published results. The American Medical Association guidelines allows for a variation of 10% or 5° of total ROM to validate a proper CROM measurement method [10,17], and the results acquired using our method was in accordance with these guidelines.

While the subjects sat upright in a straight-backed chair with their spine pressed against the back of the chair to reduce thoracic motion, the single marker on the chest measured approximately 2–3° of motion of the trunk. We analyzed data from only a single marker on the chest and detected little thoracic motion in the same direction of rotation, that is, approximately 2°. The MMD could evaluate and correct small thoracic motion. The MMD provides increased accuracy that aids in correcting the error generated by thoracic motion.

To our knowledge, only a few studies have analyzed angular velocities of motion of the cervical spine. Some have identified velocity as the most discriminant variable between controls and patients with disorders associated with whiplash [1,4]. Another study analyzed the median value of velocities and found significant differences between controls and patients [18]. Other studies suggest that reaction times and decreases in speed of motion are exhibited by people with diverse diseases. This has been confirmed in subsequent studies in which the maximum speed of neck movement is an important variable for evaluating impairments caused by neck disorders [4,6]. Polaris is capable of sampling at a rate of 60 Hz, which is sufficient for recording all volitional movement because the fastest rate of motion observed in any subject is 1.6 Hz [19]. Our device measures maximal instantaneous angular velocity. The MMD could measure the motions of healthy males in their twenties who are the one of generations having the highest ability to exercise. For this reason, we thought that the MMD could also measure motions of other generations or pathological populations technically. However, we should use stochastic filtering frameworks like particle filters if we measure more rapid motion like kinetic reflexes or athlete's motion. Our MMD was light but large in size because we had to meet the conditions necessary for the optical tracking system. In the future, the technology evolution will enable downsizing of the marker and we will be able to make the MMD smaller and lighter so that it will be possible to use in the clinical setting.

In the present study, the MMD enabled measurement of dynamic coupled CROM and maximal angular velocity of the basic movements of the cervical spine in addition to static CROM. We think that it is reasonable to conclude that these analyses can be useful for clinical evaluation in orthopedics and rehabilitation medicine.

APPENDIX

No benefits in any form have been or will be received from a commercial party related directly or indirectly to the subject of this manuscript.

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