INTRODUCTION

An unstable spine is clinically defined as the state of excessive spinal motion beyond the normal physiological limits. Muscles play an important role to provide the spinal movement and to maintain the spinal stability by increasing the bending stiffness at the same time. The issues of spinal stability controlled by the active muscular system are complicated since the numbers of muscles surrounding the spinal segments are larger than the degrees of freedom of the musculoskeletal system. Flexibility testing of in vitro studies has shown the feasibility to investigate the effects of muscle recruitments on the mechanical stability of the spine [1]. However, the “load-displacement” property of the spine would not reveal the active roles of the muscles in controlling the spinal stability under different environments. The purpose of this study is to estimate the in vivo flexibility characteristics of the human cervical spine to quantify the spinal stability during neck movements.

METHODS

There were five healthy subjects (three males and two females, 25.2±2.6 years old) participated in this study. All subjects were right-hand dominant without neck or shoulder disorders. The collected surface electromyographic (EMG) activities (Trigno Wireless, Delsys, Boston, USA) included the sternocleidomastoid, splenious and paraspinal muscles (trapezious, and capitis groups). The subjects sat on the chair with trunk firmly restrained, and performed voluntary movement from neutral to terminal position in anterior, posterior, left, and right directions with slow movement speeds (i.e., 10s in duration). The terminal range was reached when the subject felt mild resistance. The order of tests was randomized and three trials of each test were recorded.

A three-dimensional musculoskeletal model of the cervical spine was built. The model was equipped with 26 paired muscles which were divided into the superficial (sternocleidomastoid, splenious, trapezious, and semispinalis capitis) and deep groups (suboccipital, longus capitis and colli, scalenes, erector spinae, and cervicis muscles). Muscle forces of the superficial group were determined by the muscle activation level, and the muscle forces of the deep muscles were then calculated by the EMG-assisted optimization algorithm [2]. The muscle forces (Fm) and their associated stiffness (km) were used to estimate the elastic potential energy (Um) stored in the muscles by following formula [3]:

\[ Um = F_m \Delta l_m + \frac{1}{2} k_m \Delta l_m^2 \]

where \( \Delta l_m \) is the change in muscle length from its resting length. Muscle stiffness \( k_m \) is approximated as:

\[ k_m = \frac{qF_m}{L_m} \]

where \( L_m \) is the perturbed muscle length in a given frame. The linear force–stiffness relationship was utilized to set a q of 10 [4]. Finally, the potential of the spine system at any given frame (V) is expressed as sum of the elastic energy minus the work performed on the head weight (W):

\[ V = \sum Um - \sum W \]

The changes of the potential energy along with the neck movements were computed to formulate the “energy-posture” relationship. The acquired curves in sagittal and coronal plane were merged respectively, and a quadratic polynomial fit was used to identify its characteristic. The neutral zone (NZ) was defined as the span where the slope of the curve is small than 30% of the highest slope of the curve at terminal range of neck movements.

RESULTS AND DISCUSSION

The mean ROM during the flexion, extension, left, and right side movements were 43.7±6.6°, 52.6±5.2°, 31.6±8.6°, and 33.9±6.1° respectively. The energy-posture curve generally showed increasing stiffness at greater neck movements. The potential energy was specially decreased and then increased away from the neutral posture in flexion, while the distribution was symmetric in coronal plane. (Fig. 1). The vertex point of the curve located around 20° flexion and was at the neutral position in coronal motion. The NZ was from -1.0° to 38.2° in sagittal motion, which was larger than that in coronal motion (-9.0° ~ 9.2°, Table 1).

The results indicated that: 1) the stiffness of the flexion movement is not significantly taken up until larger flexion motion, which reflects the different needs for muscle control during the flexion and extension motions since they are biomechanically different with forward center of gravity of head. 2) the healthy subjects show symmetric energy-posture relationship in coronal motion, 3) the sagittal motion is more flexible than the coronal motion.

CONCLUSIONS

This study demonstrated the normal flexibility characteristics of the human cervical spine in young healthy subjects. The normal energy-posture relationships clarify how the neuromuscular control determines the stiffness levels of cervical spine in response to movement requirements. The results suggested that the neuromuscular control provides relatively less protection during neck flexion of daily activities. The abnormal activations of neck extensors or neuromuscular control errors during frequent neck flexion could decrease the stiffness of the cervical spine, and neck disorders may occur. Further studies are needed to verify if the deviated energy-posture relationship in the sagittal motions and asymmetric relationship in the coronal motions would be found in the patients with poor head position sense or altered sensorimotor
control, which may help to specify the mechanism for the changes of cervical spine stiffness and provide references for the assessment of neck disorders.

The head neutral posture is at the zero angle. Positive angles indicate flexion and left side bending respectively.

Table 1: Flexibility characteristics of all subjects during sagittal and coronal neck movements.

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<thead>
<tr>
<th></th>
<th>Sagittal plane</th>
<th>Coronal plane</th>
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<tbody>
<tr>
<td>Vertex position (°)</td>
<td>20.2±4.5</td>
<td>0.8±1.6</td>
</tr>
<tr>
<td>Neutral zone (°)</td>
<td>37.7±5.6</td>
<td>17.8±4.0</td>
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REFERENCES