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A wearable inertial system to assess the cervical spine mobility: Comparison with an optoelectronic-based motion capture evaluation

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ABSTRACT

In clinical settings, the cervical range of motion (ROM) is commonly used to assess cervical spine function. This study aimed at assessing cervical spine mobility based on head and thorax kinematics measured with a wearable inertial system (WS). Sequences of imposed active head movements (lateral bending, axial rotation and flexion–extension) were recorded in ten controls and 13 patients who had undergone an arthrodesis. Orientation of the head relative to the thorax was computed in terms of 3D helical angles and compared with the values obtained using an optoelectronic reference system (RS). Movement patterns from WS and RS showed excellent concurrent validity (CMC up to 1.00), but presented slight differences of bias (mean bias $< 2.5^{\circ}$) and dispersion (mean dispersion $< 4.2^{\circ}$). ROM obtained using WS also showed some differences compared to RS (mean difference $< 5.7^{\circ}$), within the range of those reported in literature. WS enabled the observation of the same significant differences between controls and patients as RS. Moreover, ROM from WS presented good test–retest repeatability (ICC between 0.63 and 0.99 and SEM $< 6.2^{\circ}$). In conclusion, WS can provide angles and ROM comparable to those obtained with RS and relevant for the cervical assessment after treatment.

1. Introduction

The cervical spine is the most mobile region of the spine, providing the head with a large range of motion. Pathologies can affect the cervical mobility, interfering with the subject's daily living. Nowadays, different treatments are proposed to decrease pain and restore mobility. It is thus crucial to have efficient evaluation tools to choose the appropriate treatment and verify the benefits of this treatment. While clinical questionnaires or scales can give a subjective evaluation of pain, the measurement or evaluation of the range of motion of the cervical spine is used in clinical settings to quantify physical disability [1–4].

The anatomy of the cervical spine and the "resulting coupled movements" make the measurement of cervical range of motion challenging [2]. These coupled movements refer to the associate movement induced during movement targeted around one axis, e.g. around the medio-lateral axis, flexion is considered as the *primary movement* while simultaneous lateral bending and axial rotation are the *associate movements* [5,6]. Different methods have been proposed to measure 3D cervical range of motion. Ultrasonic techniques [7,8], electromagnetic tracker [9,10] or optical motion capture [11,12] are accurate methods, but are restricted to a laboratory environment, require experienced staff and those systems are expensive. These drawbacks limit their applicability to a clinical routine. An electrogoniometer [13,14] can be used in a medical office, but such a system is still too cumbersome to allow measurement of daily activities. With the recent development in MEMS sensor technology, wearable inertial sensors have been proposed to overcome the main limitations of classical motion capture systems: they are simple to use and commercially available, their price is substantially lower and they enable field measurement [15,16].

Range of motion of the cervical spine can be obtained from sensors placed on head and thorax. With inertial sensors, acceleration and angular velocity are measured and processed to compute orientation information. However, due to sensor noise and integration drift, the obtained orientation may suffer from inaccuracy. The quality of the computed orientation can be improved by sensors fusion [17,18], as well as the addition of anatomical or movement constraints [19–21]. Fusion of inertial and magnetic sensors was

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used by Jasiewicz et al. [5] to assess the suitability of wearable sensors to measure head movement. Recently, Theobald et al. [22] studied different locations for the placements of inertial and magnetic sensors to measure the cervical range of motion. Although these two studies aimed at measuring cervical movement for the assessment of neck pain, their investigations were limited to control subjects. Even if 3D sensors were used, the analysis was 2D and range of movement was reported for the primary component of movement but not for the associate movements. Moreover, magnetic sensors, present in most buildings, are sensitive to ferromagnetic material.

This study aimed at providing a methodology based on wearable inertial sensors that can be used easily in clinical settings for objective assessment of cervical mobility. The proposed method was based on the fusion of inertial signals and movement constraints to evaluate reliably 3D kinematics of the cervical spine. The concurrent validity of this inertial wearable system to determine the cervical range of movement (ROM) against an optoelectronic reference system was assessed during active movements in a laboratory on control subjects and patients treated with cervical arthrodesis.

2. Methods

2.1. Subjects

Ten control subjects (average age of 35 years, from 23 to 52 years) and 13 patients (average age of 50 years, from 36 to 65 years) were enrolled. Control subjects did not display any history of cervical disorder or pain. The patients had suffered from cervical disc disease, which was treated by arthrodesis at different levels (C4–C5, C5–C6 or C6–C7), at least one year prior to the measurement. Even if arthrodesis is a common surgery for cervical disc disease, it has been shown that, after surgery, patients present limitations in mobility compared to controls [23]. We assumed thus that there was a clinical difference in mobility between the patients and the controls. Ethical approval was given by the institutional ethics committee and all participants gave informed and signed consent prior to the measurements.

2.2. Measurement systems

The wearable system (WS, Fig. 1b) included two inertial sensors linked to a light datalogger (Physilog®, BioAGM, CH) worn at the waist. Each inertial sensor included a triaxial gyroscope ($\pm 600^{\circ}$/s) and a triaxial accelerometer (± 5 g). They were fixed on the forehead and on the sternum using dermatological patches (Fig. 1a). The placement on the forehead was showed to provide repeatable angle measurement [22] and the sensor attached to the sternum was previously used in several studies, in particular to measure upper extremity kinematics using a functionally interpretable local coordinate systems [24]. The angular velocity and acceleration signals were recorded at 200 Hz.

The optoelectronic system (Vicon T40S, Oxford Metrics, UK) was used as reference system (RS). It was composed of eight infrared cameras acquiring the trajectories of reflective markers at 200 Hz. As the aim of this study was to compare the outputs of two measurement systems with their own protocols, the markers were attached on the body, as it would be done for the evaluation of the cervical mobility using a camera-based system [12]. A four-marker cluster was attached to the head with a helmet [12] and four markers were glued on the thorax: on the sternal manubrium, the xyphoid process and the spinous processes of the second and seventh thoracic vertebras [25] (Fig. 1a).

2.3. Measurement protocol

Participants were asked to perform active head movements recorded simultaneously by WS and RS. They were seated, the head stabilised in a reference posture, i.e. still, straight head and looking forwards. After a warm-up, they were asked to perform three head movement tasks: flexion/extension (*FE*), right/left axial rotation (*AR*) and right/left lateral bending (*LB*). For each task, the subject started in the reference posture, moved in one direction, moved in the opposite direction, moved back in the first direction, and return again to the reference posture (e.g. for a *FE* task, the patient was invited to flex, extend, flex the head and then return to the reference posture). Two modalities of execution were required for each task: the *Amplitude modality* for which the subject was asked to move their head as best they could [6] and the *Speed modality* with the instruction to move the head as fast as possible, both without pain. Two trials were recorded for each movement.

Inertial sensors measure kinematic data relative to their own local frames. Usually, a functional calibration is performed to align the sensor with the segment anatomical frame in order to remove orientation errors due to the positioning of the sensors on the participant [24,26]. For this purpose, subjects were asked to perform a functional calibration task (*FC*) consisting of a standing still posture, faced forward, for ten seconds and five flexions of the trunk with the head straight (i.e. avoiding head lateral flexion) (Fig. 1c).

2.4. Data processing

Custom procedures were written in Matlab R2012a (The Matworks, Natick, MA, USA) to compute joint angles given by the two systems and to extract the ROM of primary and associated movements from each task.

For WS, the 3D orientation R_{WS}^{FC} of the cervical spine (head relative to the thorax) was estimated from the inertial sensors signals. First accelerations and angular velocities were expressed in their segment anatomical frame defined by the functional calibration task. The procedure is similar to the method proposed by Favre et al. [26] for knee measurement. First, for the head and thorax, the inferior–superior axis (y) was defined along the gravity vector measured by the accelerometer during the standing posture of *FC*. The medio-lateral axis (z) was defined by the main axis of angular velocity during the trunk flexion of *FC*, and the x axis was oriented so that a right-handed frame was constructed (Fig. 1a) [see Appendix A2 for details]. The gravity vector and the main axis of trunk flexion around the hip were chosen as they have been shown to be the posture and movement inducing the lower dispersion for the thorax frame definition [24]. For the head, the same definition were used, assuming that its vertical axis corresponds to the absolute vertical axis during the standing task, and that it rotates around its mediolateral axis during the trunk flexion of the functional calibration task.

Subsequently, the orientation of the two segments was computed in the fixed reference frame (*XYZ*) using a fusion algorithm based on accelerations and angular velocities [17,19]. This fusion included a quaternion-based integration of the angular velocity and an interpolated correction of the orientation by deriving the inclination (angle with the vertical axis) from the acceleration during static periods. Moreover, a second correction of the orientation was applied by assuming no bias in the heading angle (angle around the vertical axis) between the initial and final reference posture. Finally, the orientation of the cervical spine was estimated from the orientation of the head relative to the orientation of the thorax. Details are given in Appendix A1.

For RS, the 3D orientation R_{RS}^{MC} of the cervical spine (head relative to the thorax) was estimated from the trajectories of the marker clusters (*MC*) on the head and thorax segments. First, marker