Use of a Multibody Model for Determination of the 3D Human Spine Posture from Wearable Inertial Sensors

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EXTENDED ABSTRACT

Because spine curvature influences vertebral loading and factor-of-risk patterns for neutral standing and other activities [1], determination of the correct location and orientation of the spine bodies is essential for effective prevention, evaluation and treatment of spinal disorders. In this field, the X-ray image is still used as "gold standard", and remains an essential tool for the diagnosis of spinal abnormalities/deformities, as it accurately reveals the degree and severity of the problem. However, this technology is not accessible for most clinicians, and diagnostic X-ray exposure increases the risk of cancer [2]. Nowadays, there is a wide range of spine posture and motion assessment tools available for clinical use [3]. Even if optoelectronic systems can yield very accurate results, surface markers usually do not offer information on spine rotations. Recent developments in microelectromechanical systems (MEMS) have caused a renewed interest in the use of Inertial Measurement Units (IMUs) to record three-dimensional (3D) human posture and motion [4].

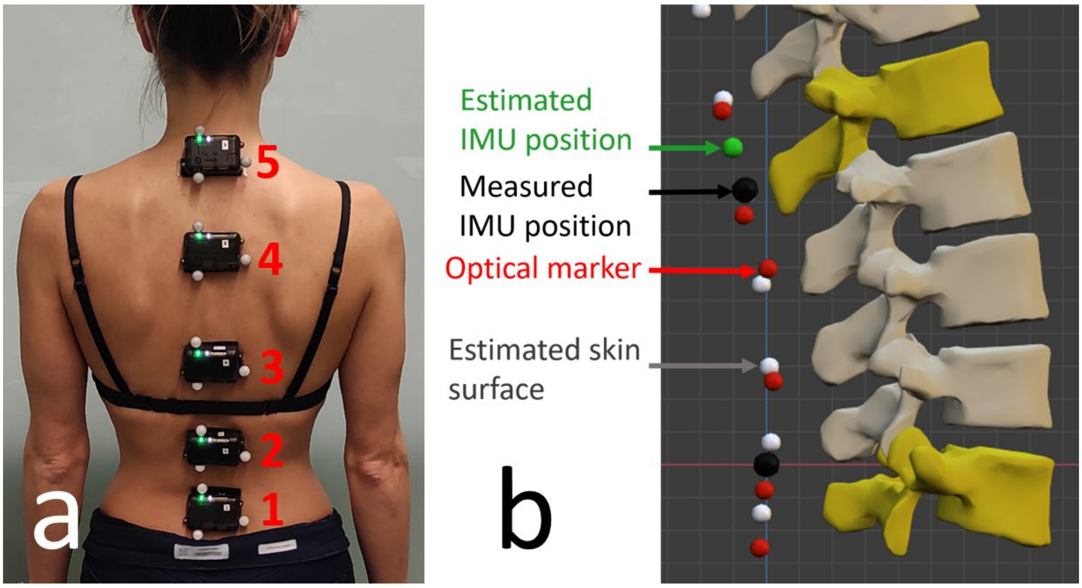

Figure 1: a) IMUs attached to the subject's body and markers attached to the IMUs; b) Multibody model of the spine.

IMUs estimate their own orientation within an Earth-fixed frame by using sensor fusion algorithms, such as Madgwick's algorithm [5] or the extended Kalman filter (EKF). These algorithms provide an estimate of the orientation by combining the information coming from the triaxial accelerometers, gyroscopes and magnetometers present in the IMU. Because the spinal curvature is soft, i.e. it can be approximated using a cubic spline [6], and the relative orientations of vertabrae are limited by anatomical restrictions, a reduced number of sensors can be used to estimate a higher number of vertebral orientations by extrapolation with the help of a multibody model of the spine. In this work, the location and orientation of the 17 vertebrae constituting the thoracolumbar region of the spine were estimated and compared from different sensor configurations (varying the number of sensors from 3 to 5). Calibration of the IMUs, angular offsets, gender differences and scaling difficulties were addressed in this study to achieve an accurate 3D-representation of the spine. To validate the approach and evaluate the accuracy and consistency issues due to IMU measurements, closely related to sensor calibration and magnetometer sensitivity [7], [8], three optical reflective markers were attached to each inertial sensor (Fig. 1a). The locations of the IMUs provided by the optical motion capture system (OPT) were compared with their estimated locations based on the readings from the IMUs and the spine multibody model. Additionally, the proposed method can be applied by using the orientations obtained from the markers instead of those obtained from the IMUs themselves, thus offering both an evaluation of the orientations provided by the IMUs and a new configuration of markers to estimate the missing information on spine rotations observed by using other skin-attached marker configurations.

To validate the approach and the correct location of the bodies, the estimated positions of the sensors using the multibody model (green dots in Fig. 1b) and the inertial measurement system were compared with those obtained from the optical system (black dots in Fig. 1b) using the three markers attached to each IMU (red dots in Fig. 1b). The position of IMU #1 was set as the origin of the two systems, and the position errors corresponding to IMUs #2, #3, #4 and #5, four control points of the 3D spline defined by the spine, were determined for nine healthy subjects with the two motion capture systems (IMU and OPT) and the several sensor configurations (Fig. 2).

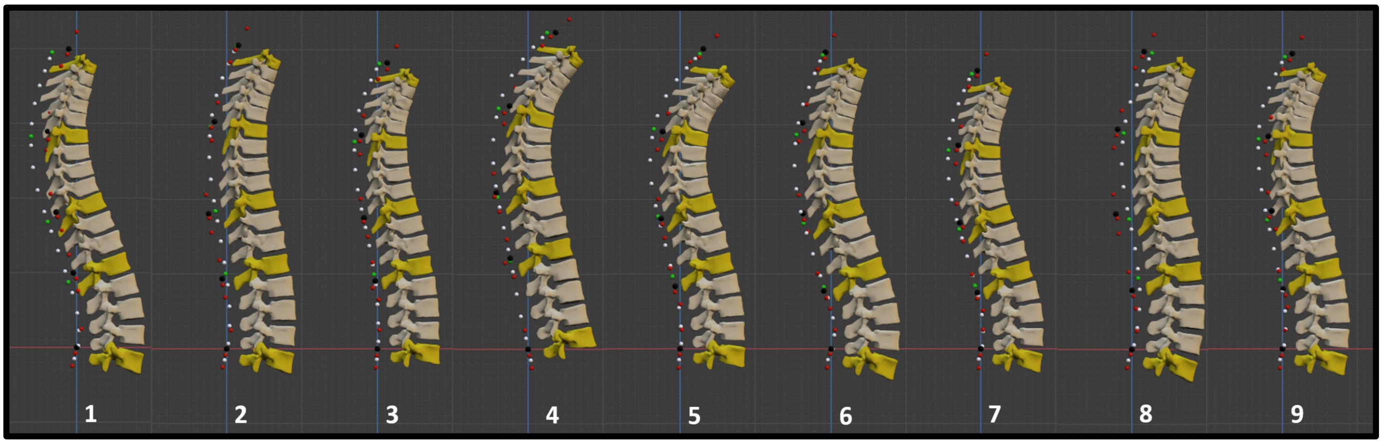

Figure 2: Lateral view of the nine 3D spine postures obtained with the inertial system and five sensors.

Obtaining the sensor orientations from the optical system, the mean errors were 1.05 cm using 4 or 5 sensors, and 1.53 cm using 3 sensors. Obtaining the sensor orientations from the inertial system, the errors showed slightly higher values, with a minimum mean error of 1.23 cm using 4 IMUs, and mean errors of 1.40 cm using 5 IMUs and 1.31 cm using 3 IMUs. The mean error in the location of vertebra T1, the last body of the open kinematic chain, was 0.84 cm using 5 IMUs and the optical system. With the other configurations (either with OPT or IMU), the error at T1 was found to be between 1.0 cm and 1.37 cm. The mean length of the spine measured along the skin of the subjects was 40.8 cm.

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