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Short communication

Three-dimensional primary and coupled range of motions and movement coordination of the pelvis, lumbar and thoracic spine in standing posture using inertial tracking device

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Evaluation of spinal range of motions (RoMs) and movement coordination between its segments (thorax, lumbar, and pelvis) has clinical and biomechanical implications. Previous studies have not recorded three-dimensional primary/coupled motions of all spinal segments simultaneously. Moreover, magnitude/direction of the coupled motions of the thorax/pelvis in standing posture and lumbopelvic rhythms in the frontal/transverse planes have not been investigated. This study, hence, used an inertial tracking device to measure T1, T5, T12, total (T1-T12) thoracic, lower (T5-T12) and upper (T1-T5) thoracic, lumbar (T12-S1), and pelvis primary and coupled RoMs as well as their movement coordination in all anatomical planes/directions in twenty-two healthy individuals. RoMs were statistically compared between the anatomical planes and spinal segments as well as with available data in the literature. The spine had different primary RoMs in different planes/directions (flexion: lumbar: 55.4 ± 12.4°, pelvis: 42.8 ± 21.6°, and T1-T12 thoracic: 19.9 ± 6.4°, extension: lumbar: 23.4 ± 10.1°, thoracic: 11.7 ± 3.4°, and pelvis: 10.2 ± 6.4°, left/right lateral bending: thoracic: 24.5 ± 7.4°/26.5 ± 6.1°, lumbar: 16.4 ± 7.2°/18.3 ± 5.7°, and pelvis: 11.0 ± 4.4°/9.3 ± 6.2°, and left/right axial rotation: thoracic: 33.5 ± 10.0°/37.1 ± 11.7°, pelvis: 31.6 ± 12.5°/27.2 ± 12.0° and lumbar: 7.5 ± 4.5°/9.2 ± 7.3°). Pelvis, lumbar and thoracic spine had different/varying contributions/rhythms to generate total trunk (T1) movement, both within and between planes. Pattern of the coupled motions was inconsistent between subjects but side bending was generally associated with twisting to the same side at the thoracic spine and to the opposite side at the lumbar spine.

1. Introduction

Due to its varying curvatures, activations/co-activations of muscles, and passive ligamentous tensions, the spine experiences complex physiological movements. For instance, any primary movement in an anatomical plane is associated, according to *in vivo* imaging investigations, with out-of-plane coupled motions (rotations) at the lumbar (Pearcy, 1985) and thoracic (Fujimori et al., 2012, 2014) levels. Specific characteristic of the coupled motions is intricate and controversial (Legaspi and Edmond, 2007; Sizer et al., 2007); e.g., side bending and axial rotations have been reported to be coupled to the same side, to the opposite side, to vary depending on the spinal level, and to be inconsistent (Huijbregts, 2004; Legaspi and Edmond, 2007; Sizer et al., 2007).

Despite such complexities, evaluation of the spinal motions has clinical and biomechanical implications. As spine diseases cause abnormal motions, clinical assessments/classifications of patients usually include a quantitative evaluation of the spine kinematics (Marras et al., 1993, 1999). Such evaluations can be as simple as measuring RoMs (McGregor et al., 1997) or other complex quantifications such as lumbopelvic rhythm (e.g., Esola et al., 1996; Granata and Sanford, 2000; Shojaei et al., 2017) and/or coupled motions (Legaspi and Edmond, 2007; Sizer et al., 2007). Collectively, such motion analyses can serve for patient discrimination and subsequent diagnostic/prognostic and treatment/manual therapy purposes (Cook and Showalter, 2004; Legaspi and Edmond, 2007; McGregor et al., 1997). Moreover, in musculoskeletal biomechanical models, measurement of primary/coupled rotations is essential for calculations of both external (e.g., gravity) and internal (e.g., active-passive tissue) moments (Arjmand and Shirazi-Adl, 2006; Arjmand et al., 2010; 2011, 2012; Bassani et al., 2017; Bruno et al., 2015; Ghezelbash et al., 2016; Hajihosseinali et al., 2014; Ignasiak et al., 2016).

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Although affected by errors from inter sensor-skin-vertebra movements, inertial tracking devices have several advantages over other skin-surface devices for being source-less (no cameras), low-cost, light, portable, and easy-to-use. Accuracy of inertial sensors has been tested by comparing their measurements for angular movements with those of the optical or electromagnetic devices (e.g., Ferrari et al., 2010; Godwin et al., 2009; Goodvin et al., 2006; Ha et al., 2013; Nüesch et al., 2017); yet they have not been used for comprehensive recordings of the complex three-dimensional motions of the spine. Inertial sensors were used to measure spinal motion during submaximal sitting-standing movements (Goodvin et al., 2006) or to measure three-dimensional RoMs of only lumbar spine (Ha et al., 2013). We recently used an inertial tracking device for measurement of the primary RoMs of the pelvis, lumbar, and thoracic spine (Hajibozorgi and Arjmand, 2016; Tafazzol et al., 2014) in the sagittal plane alone and for measurement of spine kinematics during various submaximal reaching and lifting activities (Gholipour and Arjmand, 2016).

Use of inertial sensors in the previous studies has therefore been limited to evaluation of sagittal plane movements (Hajibozorgi and Arjmand, 2016; Tafazzol et al., 2014), one region of the spine (Ha et al., 2013), or submaximal activities (Gholipour and Arjmand, 2016; Goodvin et al., 2006). Moreover, none of the previous investigations have recorded three-dimensional principal/coupled RoMs and movements of all spinal segments (thorax, lumbar, and pelvis) simultaneously. Magnitude and direction of the coupled motions of the thoracic spine and pelvis in unconstrained standing posture have not been investigated. The present study hence aims to use an inertial tracking device to:

(1) Measure T1, T5, T12, total (T1-T12) thoracic, lower (T5-T12) and upper (T1-T5) thoracic, lumbar (T12-S1), and pelvis primary and coupled RoMs in all anatomical planes and directions (flexion, extension, left/right lateral bending, and left/right axial rotation) during unconstrained standing posture in healthy individuals.
(2) Measure pelvis, lumbar and thoracic spine angular movements (from the relaxed upright posture to full RoM at different intervals) in different anatomical planes/directions as well as their movement rhythms and coordination.
(3) Perform a throughout comparison of the measured RoMs with available data in the literature.

2. Method

Four inertial sensors (Xsens MTx, Xsens Technologies, Enschede, Netherlands) were used to capture the three-dimensional rotations of the pelvis, lumbar and thoracic spine (Gholipour and Arjmand, 2016; Hajibozorgi and Arjmand, 2016; Tafazzol et al., 2014) (Supplementary materials 1). Twenty-two young healthy male students with no recent back, hip or knee complications volunteered. Their mean ± standard deviation age, body mass, height, and body mass index (BMI) were, respectively, 24.8 ± 1.0 years (range: 24–28), 71.5 ± 10.0 kg (50–92), 178.0 ± 5.4 cm (165–190), and 22.5 ± 2.7 kg/m^2 (17–29). They signed an informed consent form after being familiarized with the test. Sensors were securely attached to the overlying skin of the T1, T5, T12, and S1 spinous processes (Supplementary materials 1). Subjects were requested to, freely and to their maximum voluntary RoM, flex forward and extend backward in the sagittal plane, bend to left and right in the frontal plane, and twist to left and right in the horizontal plane from a neutral relaxed upright position with their feet shoulder width apart and their knees extended (three trials). Subjects were instructed to move slowly at their own pace (4–5 s to reach full RoM). Details on the methodology used to measured 3D angular movements of each spinal segment are provided in Supplementary materials 1. Paired

Table 1
Means and standard deviations (SD) of the primary and coupled range of motions (RoMs) (in degrees) of the pelvis (S1), lumbar (T12-S1), upper thoracic (T1-T5), lower thoracic (T5-T12), and total thoracic (T1-T12) in different anatomical planes and directions (bold values are the primary RoMs). Flexion, left lateral bending, and left axial rotation directions are positive and extension, right lateral bending and right axial rotation directions are negative as indicated in Supplementary materials 1.

		Upper thoracic (T1-T5)			Lower thoracic (T5-T12)			Total thoracic (T1-T12)			Lumbar (T12-S1)			Pelvis (S1)		
		Flexion	Bending	Rotation	Flexion	Bending	Rotation	Flexion	Bending	Rotation	Flexion	Bending	Rotation	Flexion	Bending	Rotation
Flexion (+)	Mean	**4.2**	2.1	1.9	**14.9**	−3.4	−2.2	**19.9**	−4.7	0.7	**55.4**	6.0	1.9	**42.8**	−1.5	−1.1
	SD	3.4	3.7	1.7	5.2	2.2	4.8	6.4	5.8	5.0	12.4	7.2	6.4	21.6	4.4	6.7
Extension (−)	Mean	**−10.1**	2.6	−3.7	**−5.4**	−2.6	4.3	**−11.7**	−2.6	2.9	**−23.4**	1.7	−3.9	**−10.2**	1.0	2.9
	SD	6.7	2.9	2.2	4.5	2.8	3.0	3.4	3.9	3.4	10.1	4.8	5.5	6.4	3.2	3.6
Left lateral bending (+)	Mean	−0.5	**6.3**	0.2	1.0	**18.4**	3.4	−1.9	**24.5**	4.3	4.8	**16.4**	−1.7	−1.8	**11.0**	−2.6
	SD	2.4	3.2	2.9	4.8	6.1	5.0	5.4	7.4	6.2	5.2	7.2	4.2	5.6	4.4	6.5
Right lateral bending (−)	Mean	−4.6	**−6.6**	−3.8	3.5	**−21.0**	1.1	−3.1	**−26.5**	−4.9	3.4	**−18.3**	0.7	−0.7	**−9.3**	5.7
	SD	2.9	4.9	3.3	2.8	5.4	4.1	6.6	6.1	6.2	6.8	5.7	4.6	6.0	6.2	3.9
Left axial rotation (+)	Mean	−5.7	5.5	**8.8**	1.7	6.7	**24.3**	−2.1	8.4	**33.5**	−3.4	1.2	**7.5**	3.4	6.7	**31.6**
	SD	2.6	5.0	5.3	5.1	5.2	8.8	3.3	6.9	10.0	4.8	5.1	4.5	9.0	5.6	12.5
Right axial rotation (−)	Mean	−1.6	−0.4	**−17.2**	−5.9	−12.7	**−19.5**	−9.2	−14.4	**−37.1**	3.3	1.3	**−9.2**	−2.4	−1.0	**−27.2**
	SD	4.6	3.3	6.6	6.5	5.0	9.7	7.1	5.7	11.7	8.4	7.0	7.3	9.5	11.0	12.0