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Orientation of the Head and Trunk During Functional Upper Limb Movement

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Featured Application: The present study has potential applications in sport, ergonomics and clinical practice. Orientation of the head relative to the trunk may be measured in different settings using inertial sensors. This may prove important for injury prevention and for treatment of musculo-skeletal disorders affecting the neck and shoulder, both in elite and recreational athletes and in work situations. In the clinical field, this study has application for the biomechanical assessment and rehabilitation of patients with shoulder and/or cervical spine pathologies.

Abstract: Upper limb activities imply positioning of the head with respect to the visual target and may impact trunk posture. However, the postural constraints imposed on the neck remains unclear. We used kinematic analysis to compare head and trunk orientation during arm movements (pointing) with isolated movements of the head (heading). Ten right-handed healthy adults completed both experimental tasks. In the heading task, subjects directed their face toward eight visual targets placed over a wide frontal workspace. In the pointing task, subjects pointed to the same targets (each with their right arm). Movements were recorded using an electromagnetic spatial tracking system. Both orientation of the head and trunk in space (Euler angles) and orientation of the head relative to the trunk were extracted. The orientation of the head in space was closely related to target direction during both tasks. The trunk was relatively stable during heading but contributed to pointing, with leftward axial rotation. These findings illustrate that the neck compensates for trunk rotation during pointing, engaging in specific target-dependent 3D movement in order to preserve head orientation in space. Future studies may investigate neck kinematics of people experiencing neck pain in order to identify and correct inefficient movement patterns, particularly in athletes.

Keywords: kinematics; 3D orientation; neck; head; trunk; musculoskeletal disorders

1. Introduction

Neck and shoulder pain is a highly prevalent complaint, with up to 50% of the population being affected at some stage in their life [1,2]. Those participating in sporting activities involving repetitive overhead activity such as baseball, tennis and volleyball are particularly vulnerable to these kinds of musculoskeletal injuries [3–7]. Invariably, the pathophysiology of neck and shoulder pain is multifactorial and complex [1,2]. While episodes of acute pain may resolve spontaneously, a large proportion of people experience recurrent injuries or chronic discomfort [8]. Certain guidelines underscore the importance of cervical spine integrity [9,10] in sports-related neck and shoulder injuries. Nonetheless, the coordination of head relative to the trunk during upper limb gestures has received limited attention in movement science literature [9–11].

During sport or daily life activities, the neck is submitted to constraints arising from intrinsic and extrinsic requirements. On the one hand, from an anatomical perspective, the head, trunk and upper-limb are coupled via the neck-shoulder complex. Synergistic action of muscle groups extending from the head and spine across the shoulder girdle (upper trapezius, levator scapulae, sternocleidomastoid ...) contributes to upper-limb stability and movement [12] while myofascial chains further project into the forearm to generate more distal leverage [13]. Physiologically, the trunk contributes to whole body reaching movements [14] and may participate even when the targets are within the anatomical reaching distance [15]. On the other hand, task-related extrinsic requirements and the need for online sensorimotor control impose precise orientation of the head in space. Orientation of the head engages visual, vestibular and spinal neck proprioceptive systems [16–18] serving to regulate movements of the hand [19]. In particular, coordinated head and gaze orientation are thus fundamental in throwing [20,21], catching [22], and striking actions [23] common to various sports.

Despite this, there is a marked absence of studies devoted to recording and analyzing head and trunk position through the course of functional upper limb gestures during daily life or sports [11].

We propose that improved understanding of reciprocal movements between the head and trunk during arm movement may improve the management of sports-related neck and shoulder conditions [24]. The method of measurement using electromagnetic sensors and calibration of bony landmarks has proven to have sound reliability for the measurement of humero-thoracic movement as well as range of motion though the neck and trunk [25,26]. In the present study, we compare (a) simple orientation of the head toward specific targets (heading task) with (b) forward reaching gestures (pointing) towards the same set of targets. Reciprocal movements observed at the level of the head and trunk are examined in order to improve understanding of the constraints to which the neck is subjected. Our hypothesis was that functional upper limb gestures would induce thoraco-lumbar rotation and thus prompt inverse rotation of the head [24].

2. Materials and Methods

A convenience sample of 10 healthy adult participants (5 men and 5 women) was recruited. Mean age was 28.6 ± 7.1 years (range 21 to 43), with mean height 1.69 ± 0.9m (range 1.57 to 1.83), mean weight 65.9 ± 12.4kg (range 47–89) and mean body mass index (BMI) 22.9 ± 3 (range 18.8–30.8). All were right-handed and had normal or corrected-to-normal vision. Clinical examination by an experienced physiotherapist (AR) was carried out prior to the experimental procedure to rule out asymptomatic anomalies of the arm or spine. Persons having an antecedent of orthopedic or neurological pathology affecting the shoulder or cervical spine were not eligible for this study. The study protocol was approved by the committee for the protection of persons Île-de-France III (CPP-IDFIII, no. 2013-A00660-45). All participants provided informed written consent prior to commencement.

A white panel with eight colored targets (0.015m diameter) presented in a circular arrangement (0.32m radius) around a central black cross was mounted on the wall. Each target was placed at 45° intervals corresponding to trigonometric directions (0° for East, increasing counterclockwise). According to this configuration each target was designated according to the directions: North, Northeast, East, Southeast, South, Southwest, West, Northwest. Panel height was adjusted to the level of the eyes of each person on an individual basis (Figure 1a).

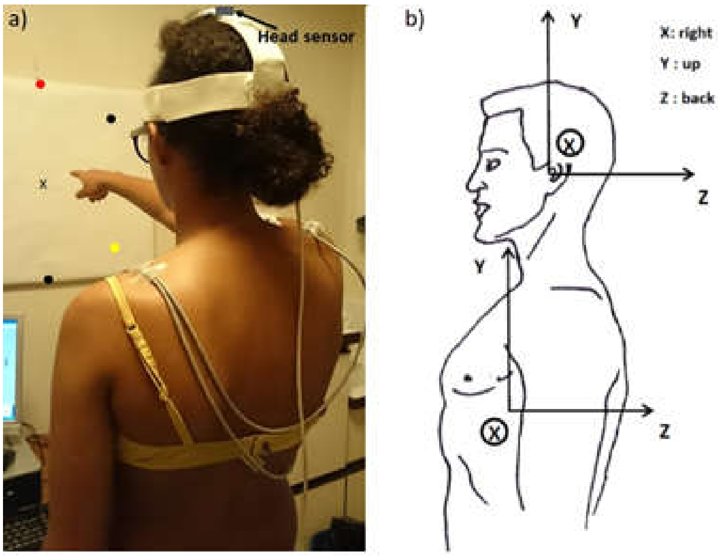

Figure 1. Experimental set-up. (**a**) Photo with the helmet (with head sensor) and targets, (**b**) schema of the reference frames.

Three electromagnetic sensors (Polhemus Fastrak) (SPACE FASTRAK, Colchester, VT, USA) were placed on each participant: one was fixed to the head using a customized helmet, another attached to the skin over the manubrium, and the third strapped to the right arm with Velcro below the insertion of the deltoid in order to monitor humero-thoracic arm motion. A fourth sensor was used to digitize the bony landmarks. Consistent with the International Shoulder Group (ISB) recommendations [27], the trunk was bounded by the xiphoid process, suprasternal notch with the C7 and T8 spinous processes. Finally, the position of the tragus and external corner of each eye were used to define canthomeatal plane (Figure 1b). The Polhemus Fastrak© transmitter, which provided the general frame of reference, was fitted to a height adjustable tripod placed in front of the participant, close to the level of the navel.

Bony landmarks of the trunk and head were calibrated by a preliminary digitization of their position using a digital stylus, and then computed in the local coordinate system of the sensor fixed on the corresponding segment. The 3D position in space of the bony landmarks of the trunk, head and arm were computed by projecting their local coordinates with the 3D position and orientation of the respective sensor. Then, reference frames were calculated for the head and trunk (with X from left to right tragus, Z from the middle between eye corners to the middle between the tragus and Y perpendicular, Figure 1b), consistent with the ISB protocol [27]. Rotation matrices between frames were calculated, then the 3D rotations were expressed by using Euler angle sequences XZY. For the purposes of this study, the Euler angle reference frame for head and trunk orientation are referred to in terms of anterior/posterior tilt (AP), lateral tilt (LA) and axial rotation (RO). By definition, the Euler angles are zero in the reference posture, positive values indicating posterior tilt, left lateral tilt, left axial rotation.

As it is known that the canthomeatal plane is inclined by reference to the horizontal [28] we aligned the reference frames of the head and trunk for each participant so that they were parallel to the global reference frame in the baseline posture, with X right, Y up and Z backward.

In the starting position, participants were required to stand upright with their trunk parallel to the panel of targets, arms by their sides. The head was positioned directly forward with the feet aligned at the malleoli along a line at 0.95m from the wall, calculated so that the eccentricity of the peripheral targets was approximately 20° by reference to the central one. The board was placed on a wall at an adjustable height so that the eyes faced the central target. The baseline posture for each participant was recorded in this starting position, while they looked forward to the central target (three trials).

Then, two separate movement tasks were examined. In the heading task, participants were instructed to turn their head towards and look at the designated target. In the pointing task, participants were instructed to indicate the designated target with their right index finger (no specific instruction was given on head posture). Upon each trial, the experimenter verbally designated the target by color. Participants were first required to focus upon the central target then, following a "go" signal from the experimenter, perform the required movement task. Posture in heading and pointing were maintained for 5s before returning to the starting position.

Participants performed three blocks of nine movements for both the heading and pointing tasks. Task order and target sequence was randomized for each participant. All movements were recorded with a sampling frequency of 30 Hz. The duration of the experimental procedure was approximately 30 minutes.

The STROBE checklist was used for the reporting [29]. Data analysis specifically examined the orientation of the trunk and the head. For each trial, data were extracted at two instants: movement initiation (initial posture prior to heading or pointing) and task completion (final posture characterized by the maximum rotation of the head or arm in heading or pointing tasks, respectively). The variables of interest were Euler angles (expressed in degrees) describing the orientation of the trunk and head in space and the head with respect to the trunk (head versus (vs.) trunk) at each time point (data presented in an Excel file "experimental data" in supplementary material). Mean and standard error (SEM) values were calculated for the three trials on each target in the respective movement tasks.

Statistical analysis of Euler angles was firstly carried out using two-way repeated measures analysis of variance (ANOVA) considering movement task (heading, pointing) and target (8 levels) as independent factors. Subsequent post-hoc comparisons were carried out using *t*-tests.

Further analysis of the effects of target direction was carried out using sinusoidal fitting. For this analysis, mean Euler angles of head orientation for the 10 participants were calculated for each target. Mean values were projected as a function of target trigonometric direction, and fitted on sinusoidal curves (Origin Software, Levenberg Marquardt algorithm). This process provides an equation for the variable y as a function of the direction of the target (Appendix A):

$$y = y0 + A \times \sin(\pi \times (\varphi - \varphi 0))$$

with the following parameters: A: amplitude; $y0$: offset; w: period; $\varphi 0$: phase shift.

According to this fitting process, the amplitude A specifies the amount of periodical variation of the angle with target direction; the offset $y0$ specifies its constant deviation by reference to the baseline posture irrespective of target direction; and phase shift φ the target direction where the maximum rotation is observed. See Appendix A for mathematical examples demonstrating the effects of changes in parameters.

The fitting process was performed separately for the three Euler angles measuring head orientation in both reference frames (head in space and head vs. trunk) in the two movement tasks (heading and pointing). Comparisons of parameters across each condition were carried out using paired *t*-tests.

Coupling between head axial rotation and lateral tilt was quantified using individual regression analyses of lateral tilt as a function of axial rotation.

3. Results

3.1. Initial Head and Trunk Posture

Mean tilt (± standard error of the mean, SEM) of the canthomeatal plane was 24.4 ± 1.3° above the horizontal in the baseline posture.

After individual alignment of the head and trunk reference frames, the angles measuring the initial orientation of the head and trunk remained close to zero, with less than 1° deviation across the different movement tasks and target conditions (no significant differences from ANOVA).

3.2. Final Head Posture in Space

Final posture of the head in space reflected the spatial position of targets in both heading and pointing (see Figure 2, filled circles). Movement towards North targets was associated with posterior tilt and South targets with anterior tilt; East targets produced right axial rotation with left lateral tilt and West targets left rotation with right lateral tilt (see Table 1). ANOVA confirmed that AP tilt, LA tilt and RO values varied with the designated target ($F_{56,7}$ = 56.8, 52.7 and 52.3 respectively; $p < 0.001$). Figure 2 shows larger modulations of the antero-posterior and axial rotation for heading than for pointing. However, the mean across targets were in both cases very small without differences between tasks at the ANOVA. A difference between heading and pointing movements was observed for lateral tilt only ($F_{56,1} = 15.4$, $p = 0.004$). The statistical effect of task can only be asserted by the significant task–target interactions for each Euler angle (F = 23.9, 15.0 and 14.4 for AP tilt, LA tilt and RO, respectively; $p < 0.001$).

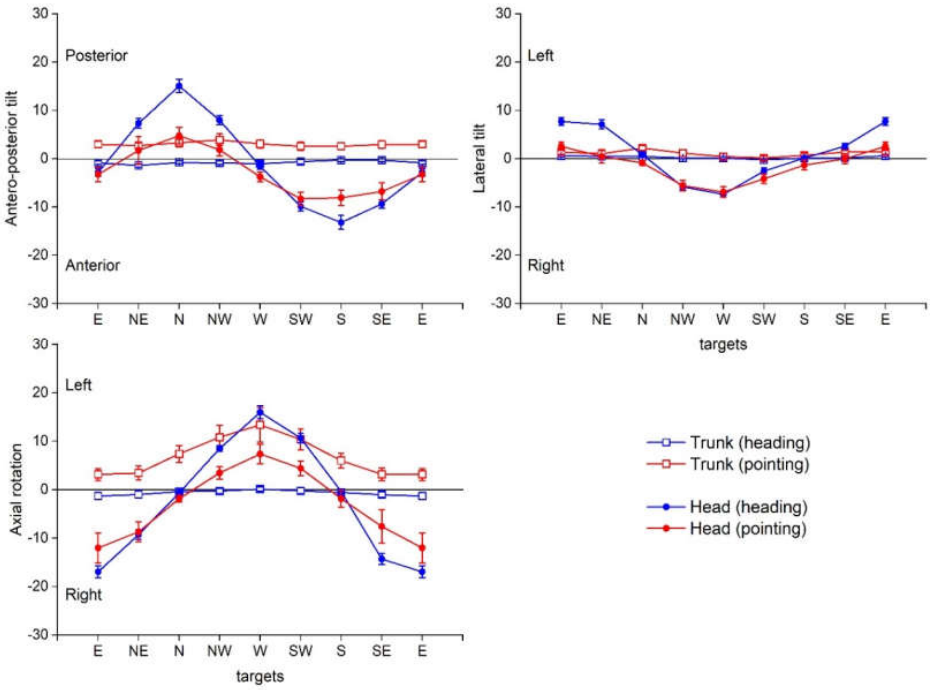

Figure 2. Variation of the head and trunk orientation in space as a function of target direction. The graphs represent the Euler angles (anterior/posterior tilt (AP), lateral tilt (LA), and axial rotation (RO)) describing the orientation of the trunk (squares) and head (circles) in space. The orientations were measured at the time of heading (blue symbols) and pointing (red symbols). Each point represents the mean ± standard error of the mean (SEM) of 10 participants.

3.3. Final Head Posture by Reference to the Trunk

Orientation of the head with respect to the trunk (Figure 3, Table 1) varied according to the target ($F_{56,7}$ = 30.1, 46.7 and 48.4 for AP, LA and RO, respectively; $p < 0.001$). Significant differences between heading and pointing were also found for AP and RO ($F_{56,1} = 5.4$, $p = 0.047$ and F = 9.7, $p = 0.014$) with large task–target interactions ($F_{56,7}$ = 8.1, 22.7 and 30.1 for AP, LA and RO respectively; $p < 0.001$).

3.4. Coupling between Lateral Bending and Rotation during Heading and Pointing

Lateral tilt of the head in space was inversely coupled with axial rotation for most participants, such that axial rotation to the left was associated with lateral tilt to the right (and vice versa). Regression analysis was significant for all participants for heading (r^2 = 0.616 to 0.924) and all except one participant for pointing (r^2 = 0.689 to 0.925, Table S1, supplementary material). We also observed inverse coupling between lateral tilt and axial rotation when head orientation was computed with respect to the trunk. Regression analyses were significant for all participants for heading (r2 = 0.592 to 0.932) but only 5 participants for pointing (r2 = 0.494 to 0.828, Table S2, supplementary material).

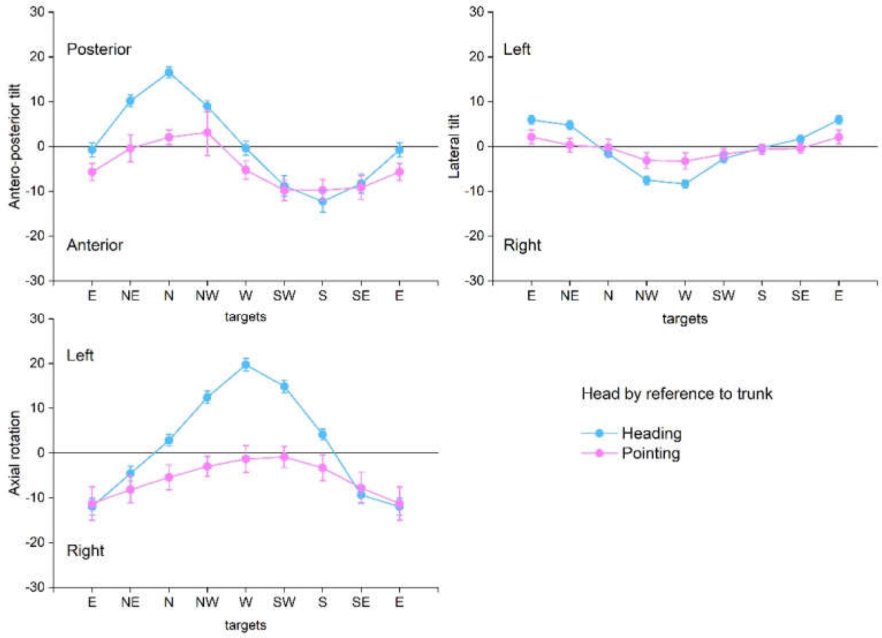

Figure 3. Variation of the head orientation by reference to the trunk as a function of target direction. The graphs represent the Euler angles (anterior/posterior tilt, lateral tilt and axial rotation) describing the orientation of the head relative to the trunk at the time of heading (blue circles) and pointing (pink circles). Each point represents the mean ± SEM of 10 participants.

Table 1. Mean values for 10 participants of Euler angles (expressed in degrees) representing the orientation of the head and trunk in space and the head by reference to the trunk (H vs. T) for the different target directions. AP: Anteroposterior tilt, LA lateral tilt, RO: axial rotation. Target directions: E: East, NE: Northeast, N: North, NW: Northwest, W: West, SW: Southwest, S: South, SE: Southeast. Data are mean ± SEM.

		HEADING							
		E	NE	N	NW	W	SW	S	SE
AP	head	−2.8 ± 0.8	7.3 ± 1.0	15.1 ± 1.3	8.0 ± 0.9	−1.6 ± 0.7	−9.9 ± 1.0	−13.2 ± 1.4	−9.4 ± 0.9
	trunk	−1.5 ± 1.6	−2.4 ± 1.6	−1.5 ± 1.4	−1.5 ± 1.5	−1.7 ± 1.6	−1.2 ± 1.6	−0.9 ± 1.6	−0.9 ± 1.5
	H vs. T	−0.7 ± 1.6	10.2 ± 1.4	16.6 ± 1.3	9.0 ± 1.2	−0.4 ± 1.6	−8.8 ± 2.3	−12.2 ± 2.4	−8.2 ± 2.2
LA	head	7.7 ± 0.8	7.1 ± 1.1	0.8 ± 0.6	−5.8 ± 0.7	−7.4 ± 0.6	−2.6 ± 0.7	0.1 ± 0.4	2.6 ± 0.6
	trunk	−0.5 ± 0.7	−0.9 ± 0.7	−0.6 ± 0.7	-0.9 ± 0.7	−1.0 ± 0.8	−1.4 ± 0.7	−0.9 ± 0.7	−0.9 ± 0.7
	H vs. T	6.0 ± 1.0	4.8 ± 1.1	−1.6 ± 0.7	−7.5 ± 1.0	−8.3 ± 0.9	−2.7 ± 1.0	−0.2 ± 0.7	1.7 ± 0.8
RO	head	−17.0 ± 1.2	−9.3 ± 1.1	−0.7 ± 0.4	8.5 ± 0.6	16.0 ± 1.3	10.6 ± 1.0	−0.4 ± 0.5	−14.3 ± 1.1
	trunk	−5.2 ± 1.1	−5.2 ± 1.2	−4.3 ± 1.5	−4.2 ± 1.4	−3.8 ± 1.7	−4.1 ± 1.6	−4.5 ± 1.4	−5.0 ± 1.3
	H vs. T	−12.0 ± 1.9	−4.6 ± 1.8	2.8 ± 1.3	12.5 ± 1.4	19.7 ± 1.4	14.9 ± 1.4	4.1 ± 1.2	−9.3 ± 1.7
		POINTING							
		E	NE	N	NW	W	SW	S	SE
AP	head	−3.3 ± 1.5	1.7 ± 2.9	4.8 ± 1.7	1.8 ± 1.2	−3.8 ± 1.0	−8.3 ± 1.4	−8.1 ± 1.6	−6.8 ± 1.8
	trunk	2.2 ± 1.6	2.2 ± 1.6	2.5 ± 1.7	3.3 ± 2.0	2.4 ± 1.9	2.0 ± 1.8	1.9 ± 1.6	2.2 ± 1.5
	H vs. T	−5.7 ± 1.9	−0.4 ± 3.0	2.1 ± 1.6	3.2 ± 5.2	−5.2 ± 2.0	−9.8 ± 2.3	−9.7 ± 2.3	−9.1 ± 2.7
LA	head	2.6 ± 0.9	0.5 ± 1.4	−0.9 ± 0.5	−5.6 ± 1.0	−6.9 ± 1.1	−4.2 ± 1.0	−1.3 ± 1.0	0.0 ± 1.0
	trunk	0.6 ± 1.1	0.4 ± 1.1	1.4 ± 1.1	0.3 ± 1.3	−0.4 ± 1.2	−0.7 ± 0.9	−0.1 ± 1.0	0.6 ± 0.8
	H vs. T	2.1 ± 1.5	0.3 ± 1.6	−0.2 ± 1.8	−3.1 ± 1.8	−3.2 ± 1.8	−1.7 ± 1.3	−0.6 ± 1.1	−0.4 ± 1.1
RO	head	−12.0 ± 3.1	−8.7 ± 2.1	−1.9 ± 0.7	3.5 ± 1.3	7.3 ± 2.0	4.4 ± 1.5	−1.9 ± 1.7	−7.6 ± 3.4
	trunk	−0.9 ± 1.8	−0.8 ± 1.9	3.4 ± 2.9	6.9 ± 3.4	9.4 ± 4.7	6.4 ± 3.2	2.0 ± 2.2	−0.8 ± 1.7
	H vs. T	−11.3 ± 3.7	−8.1 ± 3.0	−5.4 ± 2.8	−2.9 ± 2.2	−1.3 ± 3.0	−0.9 ± 2.3	−3.3 ± 2.9	−7.8 ± 3.6

3.5. Sinusoidal Fitting for Comparison between Heading and Pointing Tasks

3.5.1. Head in Space

Sinusoidal fitting for the variation of head Euler angles as a function of target direction was significant in both movement tasks (r2 = 0.86 to 0.98 for heading; r2 = 0.73 to 0.99 for pointing). Figure 4 provides a summary of these variables (for numerical values, see Table S3, supplementary material). The amplitude of sinusoidal waves describing the orientation of the head in space varied significantly according to the task and was larger for heading than pointing (*t*-test, $p < 0.001$). There was a significant negative offset which was smaller for heading (<−1°) than for pointing (−2.06 to −2.98°, Student *t* test; $p < 0.001$ for AP and LA, $p < 0.01$ for RO). This suggests that the decrease of head rotations for pointing relative to heading is due both to a decrease of the periodic variations with target directions and to a constant negative offset (i.e., a bias in anterior tilt, right tilt and right axial rotation). The mean fitted period was close to 180°. Phase shift was approximately 0° (2.5 ± 4.1°) for anteroposterior tilt (i.e., maximum for North), −90° (−92 ± 20°) for lateral tilt (maximum for East) and 90° (91 ± 7.9°) for RO (maximum for West).

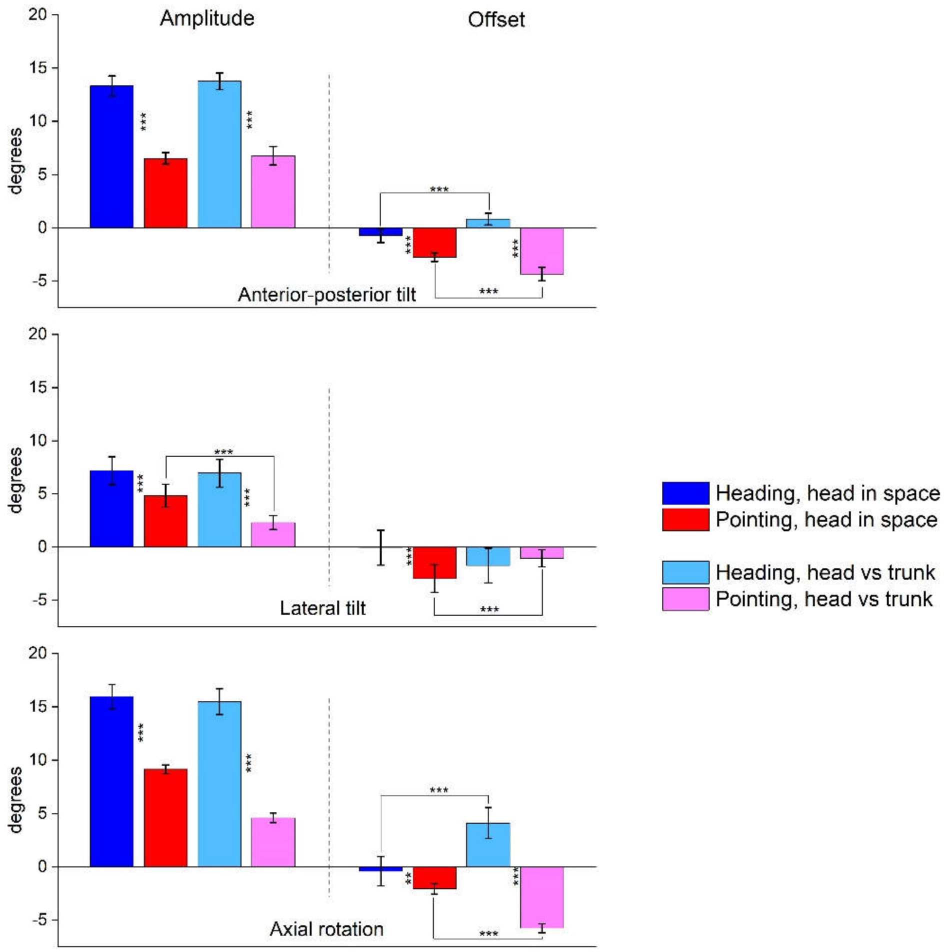

Figure 4. Variation of the parameters of the sinusoidal fitting. The graphs show the amplitude and offset of the sinusoidal fitting of the Euler angles as a function of target direction. Each histogram represents the mean ± SEM of 10 participants. Asterisks indicate statistical significance calculated by the fitting procedure (Origin Software, Levenberg Marquardt algorithm). Black asterisks vertically oriented compare tasks (pointing vs heading) and asterisks horizontally oriented compare reference frames (head orientation by reference to trunk vs space) (***: $p < 0.001$, **: $p < 0.01$, *: $p < 0.05$).

3.5.2. Head versus Trunk

The amplitude of sinusoidal waves describing the orientation of the head with respect to the trunk varied significantly with movement task (t-test, $p < 0.001$) and was larger for heading than pointing. For heading, no significant differences were found between the amplitude measured in space or with respect to the trunk. In contrast, for pointing, the amplitude of the periodic modulation of the head rotation was significantly smaller when head posture was measured by reference to the trunk (AP and LA, Student t-test; $p < 0.001$). The offset was different for the heading and pointing tasks ($p < 0.001$ for AP and RO). For heading, there was a consistent bias in leftward axial rotation (4.11 ± 1.46°). For pointing, there was a consistent anterior bias (−4.36 ± 0.62°) associated with a consistent rightward rotation (−5.75 ± 0.43°). We found significant differences between offset computed in space or head vs. trunk (for heading: AP and RO, $p < 0.001$; LA, $p < 0.05$; and pointing, AP, LA and RO $p < 0.001$). In brief, the analysis of the offset suggests that the involvement of the trunk in pointing induced complex bias on the orientation of the head relative to the trunk: it exaggerated the bias in anterior tilt and right axial rotation and reduced that in lateral tilt. The period and phase were similar to those computed for the posture of the head in space, except for a shorter period for RO during pointing (154°).

4. Discussion

The present study compared head and trunk kinematics during two experimental tasks. The heading task explicitly required subjects to orientate their head towards designated targets. For the pointing task, movements of the head were implicitly required as subjects gestured towards the same targets with their outstretched right arm.

The posture of the head in space was observed to be finely tuned to target direction, irrespective of the task. Pointing movements with the dominant right arm were associated with a posterior tilt of the trunk. Moreover, the systematic left axial rotation was indicative of participation of the trunk to the upper-limb reaching synergy, even in this relatively simple gesture. The combination of the target related spatial constraints on the head and the synergetic trunk movement in pointing induced distinct combinations of rotation (flexion-extension, lateral bending and axial rotation) at the level of the cervical spine. Our results highlight complex reciprocal movement constraints imposed upon the cervical and thoracic spine during functional upper limb movement. These findings have potential implications in the management of sports related musculoskeletal disorders of the neck and shoulder.

Target dependent head orientation in space.

Participants were observed to orientate their heads consistently toward the different targets across both heading and pointing tasks. Being able to adjust the position of one's head effectively with respect to a given target is an important component for success in various motor skills (e.g., bat and ball sports). Combined movement of the head, trunk and lower limbs for maintaining the orientation of the head in space has been previously documented in studies examining whole body locomotor tasks (e.g., walking, running, hopping . . .) [30–33] or different postural constraints involving varying trunk orientation [34]. The present study demonstrated similar tuning of the orientation of the head in space when fixating targets (heading) and when completing functional arm movement towards those targets (pointing). But the amplitude of the angles was smaller for pointing. Of course, orientation of the head with respect to the target may be assumed to support the line of sight. Shifting one's gaze generally implies rotation of the head accompanying eye movements so as to place the image on the fovea (review in [17]). During the heading task, we found that the maximal amplitude of head axial rotation was comparable to target eccentricity (i.e., 20°), suggesting that gaze orientation was mainly ensured by the head, with small eye-in-head deviations. This is not surprising given the explicit instruction for alignment of the head with the target. Amplitude of head movements was smaller during pointing and infers that foveation involved comparatively greater deviation of the visual axis with respect to the head. These observations are consistent with the known regulation of gaze direction in parallel with hand movements as a function of task requirements [16,18,19,35]. The difference we observed was quantitatively consistent with previous studies analyzing the contribution of head orientation to gaze direction [36,37].

Neck movement offsets trunk contribution to upper limb activity.

During movements of the head independent of the arm, the trunk was found to remain relatively stable. In contrast to this, the pointing task was associated with marked leftward axial rotation with more moderate posterior incline and leftward lean. This trunk rotation is most probably part of a synergy with the upper limb [38,39]. This phenomenon had a corresponding effect for the kinematics of the head with respect to the trunk. That is to say, during the heading task, variations in amplitude of the head with respect to the trunk were similar to those for the head in space. During pointing, however, the head was globally rotated toward the right relative to the trunk owing to the leftward rotation of the trunk. Importantly, then, as movement of the trunk participates in upper limb activity, the cervical spine rotates with complex 3D adjustments required to compensate trunk movement by counter-rotation [24]. At the same time, head movement with respect to the trunk was highly dependent upon target location during the pointing task. Broadly speaking, these variations in the amplitude of axial rotation and anterior head tilt were comparatively smaller than those observed in the heading task (Figure 3). For example, when pointing toward the West target, axial rotation of the head with respect to the trunk was negligible. In such an instance the movement of the trunk propelling the upper limb equally provides the necessary axial rotation for position of the head with respect to the target. The kinematic constraints on the neck are evidenced by the sinusoidal fitting analysis. For heading, the angles describing the orientation of the head relative to the trunk varied with large periodic amplitude as a function of target direction, with a small offset. In contrast, the amplitude of the periodic variation was smaller for pointing and associated by a greater offset. This suggests a greater functional rigidity of the cervical spine in this condition.

The biomechanical constraints exerted on the neck during pointing are further illustrated by the decoupling between rotation and lateral bending observed in half of the participants. The coupling between rotation and lateral bending most clearly observed during heading can be mathematical (due to Euler angles formalism), anatomical or functional. The mathematical coupling can be neglected for the relatively small angles that we observed [40]. The anatomical shape and orientation of the posterior articular facets of the cervical spine constrain the rotation of vertebrae, as demonstrated by imagery and anatomical studies [41–43]. The constraints between vertebrae vary according to the level in the cervical spine. According to [44], they lead to a homolateral coupling between rotation and lateral bending in the lower cervical spine and hetero-lateral in the upper cervical spine. Because of differences in methodologies, concluding on the effect of anatomical constraints on the global movements of the cervical spine is difficult [45–49]. It is likely that the coupling between rotation and lateral bending we observed was a functional coupling linked to the neural control of gaze direction as formalized by the Listing law [50,51]. Another likely explanation is that this movement is the result of simple biomechanical effects of the sternocleidomastoid. In effect, the different heads of this muscle establish moment arms which preferentially generate torque across these two axes [52]. The fact that coupling between axial rotation and lateral bending of the neck differed across subjects during pointing indicates that muscle activation at the level of the neck changes as one integrates upper limb movement into the process reorienting towards a target in the environment.

Implications for management of musculoskeletal complaints.

This study highlighted that the cervical spine compensates for trunk rotation during functional upper limb activity. Issues with cervical position sense are a common symptom for people experiencing neck pain or persistent symptoms after neck trauma [53,54]. We would, thus, anticipate that people with musculoskeletal neck disturbances might, therefore, experience difficulties with accommodating movements of their head when the arm is solicited, particularly for complex sporting movements. Problems in either the timing or amplitude of reciprocal head movement may be expected to further aggravate neck injuries. Our findings thus reinforce the importance of specific cervical proprioceptive retraining for musculoskeletal neck injuries [55]. In addition to the visual coordination and locomotion tasks which are typically involved in such programs (e.g., [56]), we would emphasize the need to include dynamic upper limb activities in the proprioceptive retraining process.

The decoupling between rotation and lateral bending at the neck observed for several of the subjects during the pointing movements also warrants further investigation. It is feasible that the divergent kinematics observed amongst the subjects could be related to functional anatomical characteristics. Both early degenerative changes to the vertebra or irregular activation of deep spinal musculature [57,58] may contribute to changes in cervical mobility. Changes in the properties of the musculotendinous unit (e.g., elasticity) after repetitive use can also generate novel mechanical constraints which may not be effectively compensated for by the central nervous system [59,60]. Another possibility is that participants used different postural configurations in the upper limb through the course of the pointing gesture, thereby imposing different biomechanical constraints upon the neck and shoulder girdle. For example, accurately throwing an object requires stabilizing hand orientation and movement direction, although this result may be achieved via the abundant kinematic possibilities afforded by the shoulder, elbow and wrist [61]. More detailed study of the relationship between neck posture and its relationship with intersegmental coordination of the upper limb may provide further insight into predisposing and perpetuating factors in sports related neck pain.

The current study has some limitations. We did not measure gaze orientation. Data on the variability in the cervical spine kinematics during arm heading or pointing were not available before our study, so possibilities to calculate the sample size and power our study properly were limited. Therefore, the present study should be considered an exploratory study.

5. Conclusions and Perspectives

In accordance with our major hypothesis, heading and pointing induce different trunk and head vs. trunk kinematic patterns. Arm movement during pointing was associated with trunk rotation that imposed 3D kinematic constraints on the cervical spine in order to orient the head in space.

These constraints should be considered for prevention in both sportive and professional fields and treatment of musculoskeletal symptoms, which frequently include combined neck and shoulder pain. The recommended rehabilitation programs for chronic neck pain include strengthening exercises of the neck, scapula-thoracic and shoulder muscles and proprioceptive exercises based on eye–head coordination [55,62]. Ultimately, this work should be extended to the analysis of more complex arm movements (e.g., in the context of sporting activities) in order to examine patterns of coordination across the head, neck, trunk and upper limb with the perspective of both preventing injury and enhancing athletic performance [63,64]. In particular, wearable sensor technology [65–68] could be used to detect inefficient or unsafe coordination patterns during ballistic arm movements (e.g., striking, throwing) under more ecological conditions (e.g., volleyball, American football). In the same idea, this may pave the road for innovative solutions using online feedback to assist with correcting issues such as rigid coupling or inefficient timing of counter-rotation through the cervical spine.

Supplementary Materials: The following are available online at http://www.mdpi.com/2076-3417/10/6/2115/s1: Table S1: Coupling of head lateral tilt to axial rotation (Head in space). Table S2: Coupling of head lateral tilt to axial rotation (Head versus Trunk). Table S3: Parameters of the sinusoidal fitting of the variations of head orientation as a function of target direction. Experimental data.

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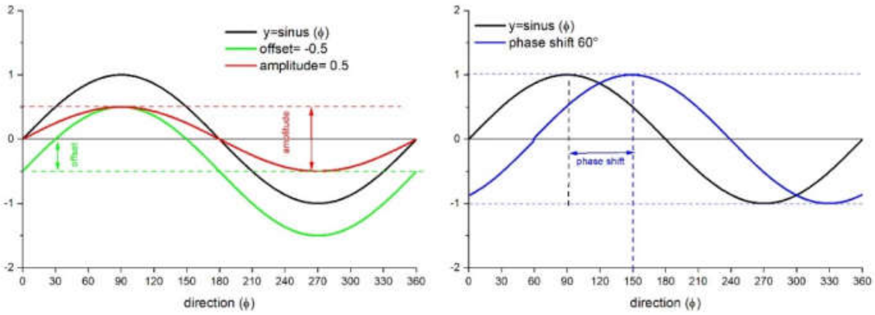
Appendix A

Mathematical representation of sinusoidal functions.



The general expression of a sinusoid function is:

$$y = y0 + A \times \sin\left(\frac{\pi}{w} \times (\varphi - \varphi 0)\right)$$

with the following parameters: A: amplitude; $y0$: offset; w: period; $\varphi 0$: phase shift. The black plain line represents the sinusoidal function $y = \sin(x)$ with the amplitude $A = 1$ and the parameters offset ($y0$) and phase shift ($\varphi 0$) are kept at 0. Colored lines represent the effect of changing the value of one parameter (values arbitrarily chosen for illustrative purpose). The left part compares the effect of decreasing the amplitude of the periodical variations ($A = 0.5$, red line) and adding a negative offset ($y0 = -0.4$, green line). The right part shows the effect of a 60° phase shift (blue line).

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