Measure of trunk 3D kinematics in sitting posture by stereophotogrammetry. Implications for seat design

Helios De Rosario*, Álvaro Page†, Rosa Porcar*, Vicente Mata‡, Juan Víctor Hoyos‡ and Begoña Mateo*
* Institute of Biomechanics of Valencia. † Dept. Applied Physics. † Dept. Mechanical Engineering.
Valencia Polytechnic University
Valencia, Spain

***Abstract*—This paper describes a method for calculating the vectorial kinematic parameters of 3D human movement by stereophotogrammetry, with special emphasis on an accurate characterization of the Instantaneous Helical Axis. That method is applied to the measure of trunk flexion in sitting posture, the results being interpreted in biomechanical terms, and compared to the mechanical design of articulated work chairs. The axes of pelvic and thoracic movements are found to be located above the seat plane, and to displace vertically as trunk is being flexed, contrary to the usually fixed axes of chairs below the seat. This leads to some discussion about ergonomic shortcomings of chair design for dynamic sitting.**

Keywords: trunk movement, sitting posture, 3D kinematics, Instantaneous Helical Axis, stereophotogrammetry.

I. INTRODUCTION

Sitting is one of the most commonly adopted postures in many workplaces and everyday activities in general; its study is therefore of crucial importance in ergonomic and biomechanical applications.

The study of sitting posture has a long history which may be traced back to the 19th century, though those early studies were chiefly prescriptive, focused on the definition of the “ideal posture” for ergonomic purposes [1]. Sitting posture has been classically characterized in static conditions, but in spite of their doubtless interest and importance, those static studies do not realistically describe the nature of sitting posture. Comfortable sitting implies mobility [1,2,3]; in fact it has been found that the lumbar angle varies in a range between the 30% and 80% of its total range of movement when sitting during 2 hours [4]. Some studies have performed continuous measurements of sagittal angles between body segments in sitting posture [3,5]. Nevertheless, even these approaches only provide a simplified description of trunk movement, as linear displacements must be considered in addition to rotations, in order to achieve a complete description of 3D movement.

The movement of a rigid body is determined by its angular velocity vector ($\boldsymbol{\omega}$) and the velocity vector of a reference point A ($\boldsymbol{v}_a$). For any other point B, its velocity $\boldsymbol{v}_b$ may be obtained from these data:

$$\boldsymbol{v}_b = \boldsymbol{v}_a + \boldsymbol{\omega} \times \boldsymbol{AB} \tag{1}$$

Alternatively, any solid movement may be defined as a screw, which is completely determined by an instantaneous helical axis (IHA) in the 3D space, the magnitude of the angular velocity (ω) and the translational velocity (v) along the axis (v vanishes in planar movement).

Among these parameters, the IHA is of special interest. Abnormal locations of the IHA in spine movements may be associated to injuries [6]; and its characterization may be also useful for the design of chairs and other seating systems which conform body movement, as recommended by ergonomic studies [7]. In previous studies it has been noted that, actually, office chair parts and body parts do not rotate around the same points [8]. However, the experimental determination of the IHA in human movement is usually difficult, due to its extreme sensitivity to errors. Even modern techniques like optoelectronics, widely used for recording human movement, introduce small errors in the position of recorded markers, which may become large errors in IHA determination.

The axes of finite displacements between two positions of anatomical bodies have been long studied [9,10,11], but unless the IHA be fixed, this approximation is not realistic. Moreover finite displacements do not have a linear behavior like instantaneous or infinitesimal displacements have [12]; therefore, while instantaneous screws may be summed for the analysis of composed or relative movements, finite screws do not have this advantage. Studies which attempt to analyze instantaneous movements often do it as an infinitesimal particular case of finite movements [13,14], unnecessarily complicating the analysis.

In this background, the aim of this paper is threefold: (a) to define an accurate direct method to measure the position and displacement of the IHA in 3D human movement; (b) to characterize with this method the forward-backward flexion movement of the trunk in sitting posture; and (c) to obtain a biomechanical interpretation of this characterization, with the purpose of applying it to seat design.

II. METHODS AND MATERIALS

A. *Instantaneous Helical Axis of a rigid marker cluster*

The kinematics of a cluster of n markers with unitary mass and velocity $\boldsymbol{v}_i$ (i = 1,2...n), may be characterized by the quantity of movement or linear momentum ($\boldsymbol{p}$), and the angular momentum in the geometric center of the cluster ($\boldsymbol{L}_g$):

$$\boldsymbol{p} = \sum_{i=1}^{n} \boldsymbol{v}_i \tag{2a}$$

$$\boldsymbol{L}_g = \sum_{i=1}^{n} \boldsymbol{r}_i \times \boldsymbol{v}_i \tag{2b}$$

where $\boldsymbol{r}_i$ is the position vector of the marker i from the geometric center of the cluster (G).

If the cluster is rigid, the kinematical parameters defined in (2a) and (2b) must follow the laws of solid movement:

$$\boldsymbol{p} = n\, \boldsymbol{v}_g \tag{3a}$$

$$\boldsymbol{L}_g = I\, \boldsymbol{\omega} \tag{3b}$$

where $\boldsymbol{v}_g$ is the velocity of the body at G, and I the inertia tensor of the cluster [15].

From (2a) and (3a) the velocity $\boldsymbol{v}_g$ may be directly calculated, and from (2b) and (3b) the angular velocity $\boldsymbol{\omega}$ may be calculated solving a system of linear equations if the cluster has at least three unaligned markers (otherwise the matrix I would be singular and the system could not be solved).

If this method is applied to a cluster of markers which is not perfectly rigid (the normal case, due to different sources of error), $\boldsymbol{v}_g$ and $\boldsymbol{\omega}$ would define the solid movement coherent with the linear and angular momentums of the cluster, and would ignore deformations, the effect of which vanishes in (2a) and (2b).

The vector $\boldsymbol{OH}$ from the origin of the reference system to the IHA may be calculated from $\boldsymbol{v}_g$ and $\boldsymbol{\omega}$, as explained by Woltring [14]:

$$\boldsymbol{OH} = \boldsymbol{OG} + (\boldsymbol{\omega} \times \boldsymbol{v}_g) / \omega^2 \tag{4}$$

where $\boldsymbol{OG}$ is the vector from the origin to G (calculated as the mean of the markers' position vectors).

Woltring [10] demonstrated that the error in the location of the helical axis in finite displacements was minimized for: (a) great rotation between initial and final position, (b) high inertia of the cluster of markers, and (c) small distance between the axis and the center of markers. These considerations can be extended to the case of instantaneous movements, changing the condition (a) by great angular velocity [14].

B. Human Trunk Model

Human trunk has been modeled as a complex chain with thorax and pelvis in its upper and lower ends, respectively (Fig. 1). Thorax and pelvis are considered rigid bodies moving with 6 degrees of freedom each, in a reference coordinate system, the origin of which is at the seat level. This is a nonparametric model which does not introduce artificial constraints to the characterization of human movement.

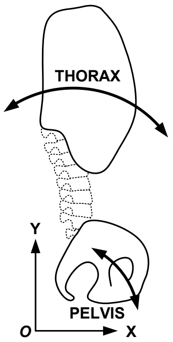

Figure 1. Human trunk model

For every position there is a flexion angle of thorax and pelvis (α_T, α_P), which are calculated as rotations from a reference upright position through finite displacement analysis. The relative flexion angle α between thorax and pelvis is also calculated, as an independent variable to which refer other functions.

Absolute movements of thorax and pelvis are characterized by their respective angular velocities and central linear velocities, as functions of the flexion angle α: $\{\boldsymbol{\omega}_T(\alpha), \boldsymbol{v}_{gT}(\alpha)\}$ for thorax, and $\{\boldsymbol{\omega}_P(\alpha), \boldsymbol{v}_{gP}(\alpha)\}$ for pelvis. The movement of the trunk relative to the pelvis is likewise characterized by its relative angular velocity and the relative linear velocity at a point, arbitrarily chosen at the origin of the reference coordinate system: $\{\boldsymbol{\omega}_R(\alpha), \boldsymbol{v}_{oR}(\alpha)\}$. Due to the linearity of instantaneous movements, relative movement vectors may be calculated as the difference of absolute vectors:

$$\boldsymbol{\omega}_R = \boldsymbol{\omega}_T - \boldsymbol{\omega}_P \tag{5a}$$

$$\boldsymbol{v}_{oR} = \boldsymbol{v}_{oT} - \boldsymbol{v}_{oP} \tag{5b}$$

where $\boldsymbol{v}_{oT}$ and $\boldsymbol{v}_{oP}$ must be previously calculated through (1).

These parameters are used for calculating the position of the absolute and relative IHA, characterized by $\boldsymbol{OH}_T(\alpha)$, $\boldsymbol{OH}_P(\alpha)$ and $\boldsymbol{OH}_R(\alpha)$ through (4). The interest of axes is that they are anatomic features, which define how are body segments articulated and may be used for modeling articulations [9,16].

C. Instruments and Procedure

Trunk movement of subjects seated on a rigid box was captured by stereophotogrammetry with two cameras recording at 25 frames per second from the back of the subjects. Thorax and pelvis were marked with 8 reflective markers of 2.5 cm diameter; iliac crests, and T12 and L5 spinous processes were also marked; three markers on the back of the seat were used to define the reference coordinate system (Fig 2). Thorax and

Figure 3. Instrumented subject

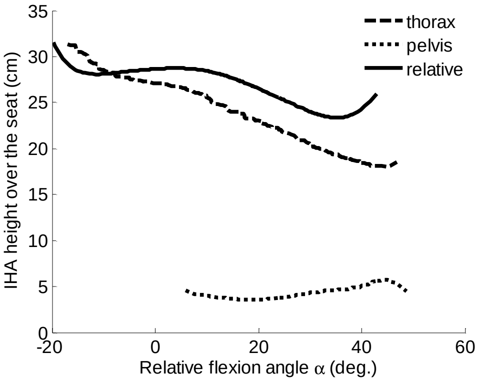

Figure 2. IHA heights variation during the flexion movement

pelvis markers were not directly attached to subject's body, but to metallic rods firmly tied to the corresponding body parts, which extended out of the body for achieving a distribution with great inertia and centered around the rotation axes, according to Woltring's criteria for minimizing the error [10].

An experiment based on that by Faiks and Reinecke [7], was carried out, with an horizontal rigid seat, and no back support, so that markers were not occluded. A group of ten volunteers (6 male, 4 female) with no reported back injuries participated in the experiment. They were recorded in the upright reference position and then performing the full range of trunk saggital flexion cyclically during approximately 20 seconds (from 4 to 7 cycles). Subjects crossed their arms on the chest to prevent that their arms interfered with the movement, but other restrictions were not introduced, so that a natural movement were recorded.

In order to reduce errors, marker trajectories and velocities were smoothed as functions of time by local cubic regression [17]. After calculating the kinematical parameters, these were again smoothed as functions of the rotated angle α, thus obtaining average functions of the different cycles of movement and further reducing errors.

D. Validation

The accuracy of this technique for identifying IHA was validated with the analysis of a controlled movement. The metallic rods used in the experiment were tied to a solid block which was articulated around an horizontal fixed axis, so that the horizontal midline of the rods was near the rotation axis. This movement was recorded as human movement was in the experiment with subjects, and the IHA orientation and location was calculated. As the axis was physically fixed, the standard deviation of the calculated orientation and location of the IHA would provide the instrumental error of the method.

III. RESULTS

A. Trajectories of Instantaneous Helical Axes

The IHA of absolute and relative movements were located over the seat plane, and in front of the anatomical landmarks, i.e., around the low region of the trunk. IHA heights over the seat plane (*Y* components of $\boldsymbol{OH}_T(\alpha)$, $\boldsymbol{OH}_P(\alpha)$ and $\boldsymbol{OH}_R(\alpha)$) varied as a function of the flexion angle α, specially for the thoracic movement. Fig. 3 shows the variation of IHA for one of the observations, and Table 1 summarizes the observed locations and displacements of IHA.

The instrumental error of the IHA had, according to the validation experiment, an standard deviation of 0.3 degrees for the orientation, and of 3 mm for its location in the *XY* plane.

B. Biomechanical Interpretation

The fact that the IHA for absolute pelvic movement is often over the seat plane reveals that the pelvis does not generally pivot on the seat, but slides backwards when flexing the trunk.

The IHA of the relative movement between thorax and pelvis is, as expected, at the lumbar region. Its vertical displacement is a consequence of the sequential movement of vertebral bodies: as lower vertebrae rotate for achieving a greater trunk flexion, the relative IHA is progressively displaced down.

The IHA of the absolute thoracic movement is determined by composition of the pelvic and relative movements: as pelvis rotates in the same direction as lumbar spine (relative movement), the IHA of thorax is located between the pelvic and relative axes, closer to the relative axis the greater the relative rotation velocity is, in comparison to that of pelvis.

C. Comparison to Axes of Articulated Seats

In spite of the variety of types of seats with articulated parts (chiefly seat pan and backrest), the vast majority incorporate mechanisms with fixed joints located below the seat. As a

TABLE I. IHA LOCATIONS AND DISPLACEMENT (CM)

Variable	Mean (SD)
Median height of the thoracic IHA	16.9 (6.0)
Median height of the pelvic IHA	2.9 (3.6)
Median height of the relative IHA	24.0 (4.8)
Median horiz. distance from relative IHA to the L5 marker	9.9 (1.6)
Range of the vertical displacement of the relative IHA	9.4 (3.5)

consequence, the IHA of the movements between the seat parts are also located below the seat plane, in contrast to the IHA of the movement between the body parts which they support.

This mismatch between IHA implies that such seats cannot “follow” human movement. Therefore, if dynamic sitting is attempted, there will be an inevitable sliding between body and seat or backrest.

IV. DISCUSSION

As subjects flexed their bodies freely, the speed of pelvic and thoracic movements varied among them. Nevertheless, the abovementioned locations of IHA and their displacement pattern were regularly observed in all subjects, what allows the definition of a consistent biomechanical model.

The mechanical design of office chairs and other types of articulated seats, however, does not match that biomechanical model. Therefore, the ergonomic recommendation of dynamic chair designs which follow the motion of the back while the seated individual changes position [7], is not usually complied. That mismatch between body and chair movements may be a reason of discomfort in dynamic sitting [5], and the fact that adjustability options are hardly used [8] could be also related.

A limitation of this study is that subjects sat on a rigid surface without backrest instead of on actual chairs or seats, for experimental reasons and for preventing that particular seat or backrest characteristics affected the results. For similar reasons, only a simple forward-backward flexion movement of the unsupported trunk has been studied, instead of more realistic but at the same time more complex movements. The information provided by these experiments in simple controlled settings, which allowed an easy interpretation, should be complemented with more complex studies in order to learn how does trunk kinematics change as a result of supported sitting with other types of movement.

V. CONCLUSION

This paper has described a vectorial method for defining the Instantaneous Helical Axes and other kinematic variables in 3D human movement through motion capture by stereophotogrammetry. That method has been applied to the analysis of trunk flexion of various subjects in sitting posture, and a regular distribution and movement pattern of axes has been found for thoracic, pelvic and relative movements. That characterization, in a simple controlled setting, may be readily interpreted in biomechanical terms (pelvic rotation and sliding on the seat, and a sequential rotation of vertebral bodies).

The comparison of that biomechanical model and the mechanics of articulated seats, office chairs in particular, has revealed that these do not match the free human movement of flexion. Further experiments in more complex settings may be performed, and once trunk kinematics in realistic environments be known, the design of chairs for dynamic sitting could be improved changing the type or location of their mechanism joints, so that the chair axes be aligned or near the axes of human movement. The procedure described in this paper may be also adapted for experimental analysis of chair kinematics, in order to compare the results with those of human movement.

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