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Toward a statistical model of the maximum reach in the sagittal plane in sitting and standing positions: Estimating the 5th percentile reach for men and women using anthropometric data from the Spanish industrial working population

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ABSTRACT

A previous kinematics model was modified in order to compute the maximum 5th percentile reach lengths for men and women in the sagittal plane in both standing and sitting positions. Shoulder height standing, fist height, shoulder height sitting, and popliteal height from the Spanish industrial working population, along with their correlation coefficients, were used as anthropometric parameters. The total variance of the model was derived in order to estimate the percentile reach envelope. Unlike well-known results, it was found that the male and female reach arcs were not concentric due to the significant difference in the acromion height between the male and female aforementioned population in standing and sitting positions. Expectedly and according to former investigations, the female maximum 5th percentile reach lengths were found to be 8.3% smaller on average than those of male. Potential applications of this research include designs of industrial workstations, equipment, tools, and products.

1. Introduction

Good designing of workstations is one of the key factors in pursuance of avoiding the worker to adopt bad or extreme postures, sustain design-imposed stresses, and endure increased joint tensions and awkward postures. Maynard (1934, cited in Das and Behara, 1998) suggested that workstation layouts should minimise the working area and that workers should use motions as short as possible in order to diminish the efforts made. In the layout design of industrial workstations, the concept of normal and maximum workspaces has generally been proposed to aid designers in making decisions about the placement of the workstation components that require manual handling (Das and Grady, 1983). Consequently, work, equipment, tools, controls, as well as other elements requiring frequent manual operation should be placed in an area (the normal working area) that can be reached and operated efficiently and safely (Barnes, 1980), whereas the ones used occasionally should not be placed beyond the maximum reach area (Health and Safety Executive, 1997).

The concepts of normal and maximum working areas were first defined by Farley (1955). The volume bounded by the fully extended arm as it pivots about the shoulder constitutes the maximum workspace; and the volume confined by the horizontal forearm as it pivots about the relaxed vertical upper arm comprises the normal working area. This approach to workspace design has been further refined, expanded, and adjusted for use in industrial settings (Squires, 1956; Das and Grady, 1983; Das and Behara, 1995; Wang, 1999).

Such strategy in the design of industrial workspaces is based on the conviction that the worker physiological cost increases as the working zone exceeds the limit from normal to maximum or from maximum to beyond maximum reach, causing fatigue, pain, and reducing productivity. Accordingly, both from an ergonomics point of view and from the worker's physiological cost point of view, it is advisable to perform tasks within the normal area whenever possible. Failing to do so, work should not exceed the maximum area, taking into account that surpassing the maximum envelope must be avoided in any cases, if possible. Sengupta and Das (2004) provided a sound basis for the significant increase of the worker physiological cost with the increase in workspace reach.

While the maximum reach envelope has been the studied by many researchers, there exist few studies that are focused on the sagittal

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plane. Hemelrijk and Sittig (1966) suggested a set of accessibility curves to calculate the maximum height of shelves in cupboards in the sagittal plane for the Dutch women population. Later, Thiberg (1970) estimated the correlation between body height and height of reach in the sagittal plane in a sample comprised of 45 Swedish men and 45 women. He worked out several regression equations that covered reaching for cupboards and shelves in different settings: placing one and both hands flat on the surface, reaching 30 cm deep from the leading edge of the surface, adding a dummy working surface, et cetera. Additionally, Grandjean (1983) proposed and published maximum limits in the sagittal plane in standing and sitting positions that became widely reproduced in many ergonomics handbooks (INSHT, 2008). All this former research was based on direct measurements, which is costly and expensive. Instead, Kee and Karwowski (2002) showed that nearly identical results to direct measurements, in terms of maximum reach envelopes, could be obtained using kinematics models. Furthermore, computing reach envelopes by means of kinematics models can be easily used to reflect on the morphologic and anthropometric changes on the population over time (Li and Xi, 1990; Bonnechère et al., 2014).

This work attempts to provide a methodology to calculate the maximum reach in the sagittal plane in both sitting and standing positions. Following the suggestion made by Behara and Das (2011) the reach length is based on the shoulder joint at the acromion. Starting from a preceding direct kinematics model of the upper limb (Álvarez and Miralles, 2015), this research places the focus on the development of these four aspects: (a) the possibility to easily manage model parameters; (b) make use of the existing anthropometric body dimensions as defined in ISO 7250-1:2008; (c) make the reach limits easily adjustable to any population irrespective of its origin or its current anthropometric development stage; and finally (d) compute the 5th percentile maximum reach for the Spanish working industrial population using the existing national anthropometric data.

2. Modelling and formulation

Modelling of the arm is based on the method proposed by Denavit and Hartenberg (1955) in which a rigid multibody is made of links connected by joints. The end-effector frame is related to the reference frame as a function of four parameters: link length, link twist, link offset and joint angle (Sciavicco and Siciliano, 2005).

The starting point is the direct kinematics model developed by Álvarez and Miralles (2015) for the right arm ($\boldsymbol{O_r}$), where a four degrees of freedom model of the arm was worked out. The model presumes that the human body is made of one-dimensional segments linked by joints. Hence, the model assumes a rigid human body where neither muscles nor tolerances are considered (Sciavicco and Siciliano, 2005) and where the joints are of the revolute type. Although models with greater number of degrees of freedom have been developed (Rebelo et al., 2012; Yang and Abdel-Malek, 2004), this model only considers four joint rotations, following the proposal of Kee and Karwowski (2002), who developed a model to compute the upper limb reach volume in sitting position.

Equation (1) relates frame 1 to frame 7 (Fig. 1) for the aforementioned model, where the point $\boldsymbol{O_r}$ is the origin of the coordinate axis for frame 1, which is placed at the acromion. Parameters q_1, q_2, q_3, and q_4 are the joint variables corresponding to each degree of freedom of the model. Physiologically, they are the angle of rotation of each joint where q_1 is the shoulder abduction/adduction with positive values for adduction, q_2 is the shoulder flexion/extension with positive values for extension, q_3 is the shoulder rotation with positive values for clockwise rotation, and q_4 is the elbow flexion/extension with positive values for extension. Parameters L_1 and L_2 are the shoulder-to-elbow length and the forearm-to-fingertip length, respectively.

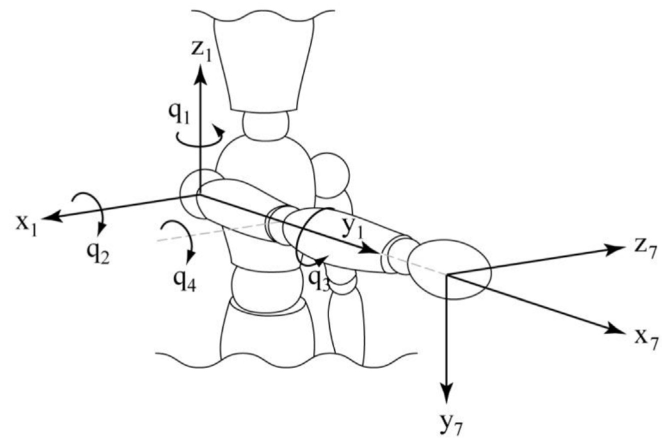

Fig. 1. Reference frame, end-effector and joint variables. Arrows show positive values for each joint variable.

$$O_r = \begin{pmatrix} (\sin q_1 \sin q_2 \cos q_3 - \cos q_1 \sin q_3) L_2 \sin q_4 \\ - \sin q_1 \cos q_2 (L_1 + L_2 \cos q_4) \\ -(\cos q_1 \sin q_2 \cos q_3 + \sin q_1 \sin q_3) L_2 \sin q_4 \\ + \cos q_1 \cos q_2 (L_1 + L_2 \cos q_4) \\ - \cos q_2 \cos q_3 L_2 \sin q_4 - \sin q_2 (L_1 + L_2 \cos q_4) \end{pmatrix} \tag{1}$$

Equation (1) encompasses all arm movements in the three-dimensional space. However, this expression can be customised to better portray the maximum arm reach in the sagittal plane. In this plane, there is no shoulder abduction/adduction so $q_1 = 0$. Additionally, the maximum reach is achieved when the arm is fully extended so $q_4 = 0$. Equation (2) is obtained after imposing these constraints in Equation (1).

$$\boldsymbol{O_r} = \begin{pmatrix} 0 \\ \cos q_2 (L_1 + L_2) \\ - \sin q_2 (L_1 + L_2) \end{pmatrix} \tag{2}$$

It is noted that the maximum reach equation thus obtained is a function of the shoulder flexion/extension angle (q_2) and the sum of the lengths of the arm and the forearm ($L_1 + L_2$). In order to facilitate the graphical representation of Equation (2), the origin of the coordinate axes ($\boldsymbol{O_r}$) is moved to the vertical orthographic projection of the acromion on the floor plane. This is done by including the height of the acromion, H_a, into the model, resulting in Equation (3).

$$\boldsymbol{O_r} = \begin{pmatrix} 0 \\ \cos q_2 (L_1 + L_2) \\ H_a - \sin q_2 (L_1 + L_2) \end{pmatrix} \tag{3}$$

2.1. Standing maximum reach

The length of the upper limb, $L_1 + L_2$ in Equation (3), is not a basic anthropometric body dimension according to ISO 7250–1:2008 and, therefore, it needs to be computed as a function of the dimensions in the aforementioned standard. Thus, two anthropometric variables are introduced into the model: S_h (shoulder height) and F_h (fist height). According to the standard, the shoulder height is defined as the vertical distance from the floor to the acromion, and the fist height as the vertical distance from the floor to the grip axis of the fist (Fig. 2). Equation (4) shows the result thus obtained when $L_1 + L_2$ is substituted by $S_h - F_h$ and H_a by S_h.

$$\boldsymbol{O_r} = \begin{pmatrix} 0 \\ \cos q_2 (S_h - F_h) \\ S_h - \sin q_2 (S_h - F_h) \end{pmatrix} \tag{4}$$