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Using kinematic reduction for studying grasping postures. An application to power and precision grasp of cylinders

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ABSTRACT

The kinematic analysis of human grasping is challenging because of the high number of degrees of freedom involved. The use of principal component and factorial analyses is proposed in the present study to reduce the hand kinematics dimensionality in the analysis of posture for ergonomic purposes, allowing for a comprehensive study without losing accuracy while also enabling velocity and acceleration analyses to be performed. A laboratory study was designed to analyse the effect of weight and diameter in the grasping posture for cylinders. This study measured the hand posture from six subjects when transporting cylinders of different weights and diameters with precision and power grasps. The hand posture was measured using a Vicon® motion-tracking system, and the principal component analysis was applied to reduce the kinematics dimensionality. Different ANOVAs were performed on the reduced kinematic variables to check the effect of weight and diameter of the cylinders, as well as that of the subject. The results show that the original twenty-three degrees of freedom of the hand were reduced to five, which were identified as *digit arching*, *closeness*, *palmar arching*, *finger adduction* and *thumb opposition*. Both cylinder diameter and weight significantly affected the precision grasping posture: diameter affects *closeness*, *palmar arching* and *opposition*, while weight affects *digit arching*, *palmar arching* and *closeness*. The power-grasping posture was mainly affected by the cylinder diameter, through *digit arching*, *closeness* and *opposition*. The grasping posture was largely affected by the subject factor and this effect couldn't be attributed only to hand size. In conclusion, this kinematic reduction allowed identifying the effect of the diameter and weight of the cylinders in a comprehensive way, being diameter more important than weight.

1. Introduction

The human hand is a complex mechanical system that allows us to perform many activities of daily living, work, and recreation. Hand posture introduces constraints on the strength that can be exerted to complete a given task (Domalain et al., 2008; Rossi et al., 2012; Shivers et al., 2002; Watanabe et al., 2005), and affects the distribution of contact pressure and comfort rating (Aldien et al., 2005; Youakim, 2009). Hand posture also affects tendon loads and excursions, and stresses on adjacent tissues such as synovial membranes and nerves (An et al., 1983; Lee et al., 2008), which is associated with the risk of developing work-related musculoskeletal disorders (WMSD) (Laoopugsin and Laoopugsin, 2012; Wells et al., 1994). When attempting to prevent WMSD, different interventions are performed, such as controlling postures, lowering the required grasp force or changing the shape and size of the grasped surface, among others (Harih, 2014; Kroemer, 1989). Traditionally, when analyzing the upper limb posture to determine the risk of developing WMSD, the focus is set on shoulder and wrist postures, although recent work has also shown interest in recording all hand joints with more detail (Baker et al., 2007a, 2007b; Lee and Jung, 2015; Wang et al., 2015, 2014).

Abbreviations: 3D, 3 dimensional; Ab/Ad, Abduction/adduction; ANOVA, Analysis of variance; CMC, Carpometacarpal; DIP, Distal interphalangeal; DoF, Degrees of freedom; F/E, Flexion/extension; HL, Hand length; HB, Hand breadth; IP, Interphalangeal; MANOVA, Multiple analysis of variance; MCP, Metacarpophalangeal; MSV, Mean square variance explained; PCA, Principal component analysis; PCi, Principal component i; PIP, Proximal interphalangeal; RKVs, Reduced kinematic variables; SD, Standard deviation; Sig., Significance level; WMSD, Work-related musculoskeletal disorders.

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Hand posture analysis is hindered by the intrinsic kinematic complexity of the hand; using all joint angles might be cumbersome for describing hand shape, and focusing only on specific parameters might limit the results (Bae, 2011; Supuk et al., 2005). Observation-based assessments are more commonly used by occupational safety and health practitioners due to their affordability (David, 2005). In this sense, some recent studies have used video recording and posture classification to describe hand posture (Hwang et al., 2010; Vergara et al., 2014; Wang et al., 2015, 2014). However, these observation-based techniques are prone to problems caused by the hands being hidden by the handled objects and by other parts of the body, are very time-consuming, and are less reliable than the methods that register joint angles directly (David, 2005), named direct methods. Among these methods, instrumented gloves and videogrammetry have been used for ergonomic applications (Baker et al., 2007a, 2007b; Endo et al., 2007; Sánchez-Margallo et al., 2014; Yun, 1993). Direct methods also allow velocities and accelerations of movements to be obtained, which are critical for the analysis of WMSD (Juul-Kristensen et al., 2001; Marras and Schoenmarklin, 1993). Yet results obtained with so many degrees of freedom (DoF) are difficult to interpret, because of the need to observe the simultaneous variation of a large number of concatenated joint angles in different planes (Bae, 2011; Supuk et al., 2005).

A recent study proposed two metrics to describe hand shape registered by direct methods in a more comprehensive way than using the angles of all DoF (Bae, 2011): *openness* indicates the positions of the fingertips based on metacarpophalangeal (MCP) joint angles, while *flatness* indicates the extent to which each finger is flat or curved, based on the proximal interphalangeal (PIP) joint angles. These metrics were employed to test the effects of object size and shape on hand shaping during grasping. Limitations are apparent, as both metrics are related only to finger MCP and PIP flexion.

Although hand motion has many DoF, not all the joint movements are independent, because of mechanical and neural coupling. Mechanical coupling is due to connections between tendons and multidigit insertions of extrinsic finger muscles (el-Badawi et al., 1995; Tubiana and Valentin, 1964; von Schroeder et al., 1990), and neural coupling comes from the innervation of multiple spinal motor neuron pools from a single cortical motor neuron (McKiernan et al., 1998; Santello et al., 2013; Schieber et al., 2001). The coordinated movements between various joints resulting from these couplings are referred to as kinematic synergies (Bernshteĭn, 1967).

Based on principal component analysis (PCA), Santello and collaborators found support for the existence of static postural synergies, so that the hand shape can be predicted using a reduced set of variables, or postural synergies (Santello and Soechting, 1998; Santello et al., 2002, 1998). PCA is a statistical procedure that uses an orthogonal transformation to transform a set of correlated variables into a smaller set of linearly uncorrelated variables called principal components (PCs). In a recent study (Thakur et al., 2008), 17 subjects were asked to perform an unconstrained haptic exploration task over 50 different objects, identifying nine PCs, i.e., synergies, that were similar across subjects and across manipulations of different objects and accounted for more than 90% of the variance in the hand postures registered throughout all tasks. It was suggested that these synergies represented the basic building blocks underlying natural hand motions and may be used to represent hand posture and movements, thereby reducing the dimensionality of the results.

Furthermore, these synergies may also be used to measure hand postures in ergonomics studies in order to improve the design of handles and other parameters of the products that affect the way they are grasped and manipulated. Previous studies have shown that object size and shape cause different grasp execution (Cuijpers et al., 2004; Domalain et al., 2008; Meulenbroek et al., 2001; Santello and Soechting, 1998): the hand adapts its aperture to the size and shape of the object in an attempt to avoid collisions, especially with the fingers; this adaptation is not uniform, but increases dramatically during the last phase of grasp execution; thick objects (envelop diameter > 4 cm) tend to be grasped with all digits, while only the thumb and the index and middle fingers are used to grasp thin objects. Fewer studies have addressed the effect of an object's weight on hand posture. Weir et al. (1991) found a small but significant effect of the weight of the object on thumb and index finger motion during prehension of a metallic dowel. A significant influence of object size and weight on grip force during manipulation has been found (Jordan et al., 2005; Kinoshita et al., 1997; Vigouroux et al., 2011) and, consequently, hand kinematics might be modified by the central nervous system to apply grip force in a more efficient way. More knowledge is therefore required about the whole hand posture while grasping objects of different weights (Lee and Jung, 2015, 2014). Finally, hand posture is expected to be dependent on the subject. One personal factor that has been repeatedly studied is the relationship between hand size (mainly hand length) and object size (Seo and Armstrong, 2008), although the way the central nervous system adapts the musculoskeletal configuration to the grasping of objects may be different for different people. In a previous study (Mora et al., 2012), hand size was in fact postulated to account for the subject effect in an artificial neural network aimed at predicting hand posture, with poor results, thus indicating that the subject effect could not be reduced to hand size.

In this work we present a method to reduce the kinematic dimensionality of the hand posture, which can be used for ergonomics analyses, so that the complexity is reduced while keeping most of the information. In particular, we applied PCA to reduce the hand kinematics while grasping cylinders, and studied the effect of the cylinder diameter and weight on the grasping posture for precision and power grasps. We also verify whether hand size is able to account for subject posture variability for these grasps.

2. Material and methods

2.1. Kinematic reduction of DoF using principal component analysis

The method proposed for the kinematic reduction is to perform a PCA based on eigenvalue decomposition of a data correlation matrix (Daffertshofer et al., 2004; Hair et al., 2009) on all the hand joint angles registered. Each observation (grasping posture) consists of a row vector of 23 variables (the hand joint angles). The correlation matrix (23 × 23) is then built with the sums of the squares and cross products from the standardized data, by setting all variances equal to one. The sample size required to be able to apply PCA should be 100 observations or larger (Hair et al., 2009); as a general rule, there should be at least 5 (recommended 10) times as many observations as the number of variables (angles registered) to be analyzed. The criterion recommended to extract the PCs is the latent root criterion in which all eigenvalues >1, so that each PC accounts for the variance of at least one of the original variables. This method is more reliable when the number of variables is between 20 and 50 (Hair et al., 2009). Prior to computation of the PCs, the joint angles should be rescaled to unit variance (Daffertshofer et al., 2004) to prevent the first modes from reflecting the joint angles with the largest amplitudes (flexion of MCP joints are expected to vary more than abduction of these joints). Communalities can be used as indicators of the reliability of the PC extraction, as they show how much of the variance in each of