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Dynamics of wrist and forearm rotations

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ABSTRACT

Human movement generally involves multiple degrees of freedom (DOF) coordinated in a graceful and seemingly effortless manner even though the underlying dynamics are generally complex. Understanding these dynamics is important because it exposes the challenges that the neuromuscular system faces in controlling movement. Despite the importance of wrist and forearm rotations in everyday life, the dynamics of movements involving wrist and forearm rotations are currently unknown.

Here we present equations of motion describing the torques required to produce movements combining flexion–extension (FE) and radial–ulnar deviation (RUD) of the wrist and pronation–supination (PS) of the forearm. The total torque is comprised of components required to overcome the effects of inertia, damping, stiffness, and gravity. Using experimentally measured kinematic data and subject-specific impedance parameters (inertia, damping, and stiffness), we evaluated movement torques to test the following hypotheses: the dynamics of wrist and forearm rotations are (1) dominated by stiffness, not inertial or damping effects, (2) significantly coupled through interaction torques due to stiffness and damping (but not inertia), and (3) too complex to be well approximated by a simple, linear model.

We found that (1) the dynamics of movements combining the wrist and forearm are similar to wrist rotations in that stiffness dominates over inertial and damping effects ($p < 0.0001$) by approximately an order of magnitude, (2) the DOF of the wrist and forearm are significantly coupled through stiffness, while interactions due to inertia and damping are small, and (3) despite the complexity of the exact equations of motion, the dynamics of wrist and forearm rotations are well approximated by a simple, linear (but still coupled) model (the mean error in predicting torque was less than 1% of the maximum torque). The exact and approximate models are presented for modeling wrist and forearm rotations in future studies.

1. Introduction

Healthy upper limb movements generally involve multiple degrees of freedom (DOF) gracefully coordinated into a single movement. Despite the apparent ease with which these movements are performed, the dynamics underlying multi-DOF movements can be complex. Understanding these dynamics is important because it exposes the challenges that the neuromuscular system must overcome to produce coordinated movement and provides insight into the deficits caused by movement disorders.

One way to characterize the dynamics that the neuromuscular system must control is to investigate the equations of motion, which specify the joint torques required to produce a desired movement. However, care must be taken because the level of complexity that the neuromuscular system must control may be substantially less than the level of complexity in the equations of motion. For example, we recently investigated the dynamics of wrist rotations combining flexion–extension (FE) and radial–ulnar deviation (RUD) and found that while the exact equations of motion underlying wrist rotations are relatively complex, they can be approximated with good accuracy by a simple, linear model (Charles and Hogan, 2011). Furthermore, while all elements of mechanical impedance (inertia, damping, and stiffness) affect wrist rotations, some effects greatly outweigh others; making comfortably paced wrist rotations requires approximately ten times more torque to overcome the passive stiffness of the wrist than the passive damping of the wrist or the inertia of the hand. In fact, the effects of passive wrist stiffness are visually observable in wrist rotation behavior (Charles and Hogan, 2010, 2012). Also, while FE and RUD are coupled (i.e., movement in one DOF generates a torque in the other DOF) through interaction torques due to all impedance elements, the interaction due to inertia is

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negligible compared to the interaction due to stiffness and damping. Thus, evaluating the equations of motion with subject-specific movement data and model parameters has provided valuable insight into the dynamics that the neuromuscular system must overcome to control wrist rotations.

In contrast, although many natural movements involve both wrist rotations (FE and RUD) and forearm rotations (PS) (Aizawa et al., 2010; Anderton and Charles, 2012; van Andel et al., 2008), the dynamics underlying movements involving both wrist and forearm rotations are currently unknown. Because the complexity of movement dynamics increases superlinearly with the number of DOF involved, the dynamics of wrist and forearm rotations are likely to be significantly more complex than (and cannot be inferred from) the dynamics of wrist or forearm rotations by themselves, and it is unclear if they can be well approximated by a simple model. Likewise, while stiffness dominates over inertial effects for wrist rotations, the inertial effects involved in shoulder and elbow (reaching) movements are significantly larger, so what (if anything) dominates the dynamics of the intermediate joint (the forearm), and by extension combinations of wrist and forearm rotations, is currently unknown. Finally, while inertial interaction torques are negligible in wrist rotations, they are significant in shoulder and elbow movements (Hollerbach and Flash, 1982), so whether the forearm is coupled to the wrist through inertial, damping, or stiffness (or not at all), is also unknown.

The purpose of this study was to reveal the dynamics that the neuromuscular system must overcome to produce movements involving both wrist and forearm rotations. Adjacent DOF (e.g., elbow flexion–extension) were excluded to maintain tractability; controlling more than 3 DOF simultaneously using visual feedback is prohibitively difficult for subjects, and the complexity of the dynamics (including the number of interactions between DOF) increases superlinearly with the number of DOF. Here we (A) present the equations of motion underlying general wrist and forearm rotations and (B) evaluate these equations of motion on individual subjects (by combining their kinematics with subject-specific impedance parameters) to test the following hypotheses: the dynamics of movements involving wrist and forearm rotations are similar to pure wrist rotations in that (1) stiffness greatly outweighs inertial or damping effects, and (2) the DOF are significantly coupled through stiffness and damping (but not inertia), but they are different from pure wrist rotations in that (3) they cannot be approximated by a simple model because of the increased complexity of 3-DOF movements.

2. Methods

2.1. Kinematic data

2.1.1. Subjects

Ten young, healthy, right-handed subjects (5 females and 5 males, ages 19–37) free from neurological and biomechanical injuries to the upper limb participated in this study. All subjects gave informed consent following procedures approved by Brigham Young University.

2.1.2. Experimental setup

Subjects were seated with the upper limb in the parasagittal plane (0° shoulder abduction and approximately 30° of shoulder flexion and 60° elbow flexion). The proximal 14 cm of the forearm rested on a support while the distal forearm, wrist and hand remained unsupported, allowing for unobstructed use of PS, FE, and RUD (Fig. 1A). Electromagnetic motion tracking sensors (trakSTAR by Ascension Technologies, Burlington, VT) were attached to the distal forearm (approximately 5 cm proximal to the wrist joint center) and atop a handle held by the subject. These sensors recorded orientation at approximately 300 Hz with a static accuracy and resolution of 0.5° and 0.1°, respectively. The sensor and handle together weighed approximately 70 g (13% of the mass of the average hand – see Section 4).Each subject was calibrated in neutral position, defined as follows. The forearm was in neutral PS when the dorsal aspect of the distal forearm (more specifically the dorsal tubercle of the radius and the dorsal-most aspect of the ulnar head) was in the parasagittal plane. The wrist was in neutral FE and RUD when the long axis of the forearm was parallel to the long axis of the third metacarpal.

2.1.3. Protocol

During the experiment the position of each DOF was communicated to the subject graphically via a computer screen in front of the subject (Fig. 1B). A cursor on the screen moved horizontally and vertically in proportion to wrist FE and RUD, respectively. A yellow line through the center of this cursor communicated the amount of PS by rotating an equal amount from the vertical (neutral position). FE and RUD targets were represented by a pattern of white circles surrounding the neutral position, while targets in PS were represented by a red line drawn through the cursor. When a target was selected the corresponding circle from the pattern changed color to indicate the required FE and RUD, while the red line assumed the target PS angle. Subjects were required to align the cursor with the target circle and their PS with the target PS (within 2°) before the next target would appear. The forearm and hand were not covered during the experiment, but the task required paying attention to the screen and the forearm and hand were sufficiently removed from the line of sight to the screen (see Fig. 1) that subjects did not pay attention to their forearm and hand.

Targets were selected to require pure PS, FE, and RUD, as well as 2- and 3-way combinations of these DOF, resulting in 26 targets surrounding neutral position. To compare between movements to different targets on the same basis, all targets required the same total movement amplitude. More specifically, each target was positioned in such a way that it could be obtained through a single 15° rotation. For example, the target requiring positive displacement in all three DOF required 8.9° in each DOF but could be obtained by a single 15° rotation (about an axis that is different from the axes of the three DOF). Requiring the same movement amplitude for all targets resulted in the unusual star-like pattern shown in Fig. 1B.

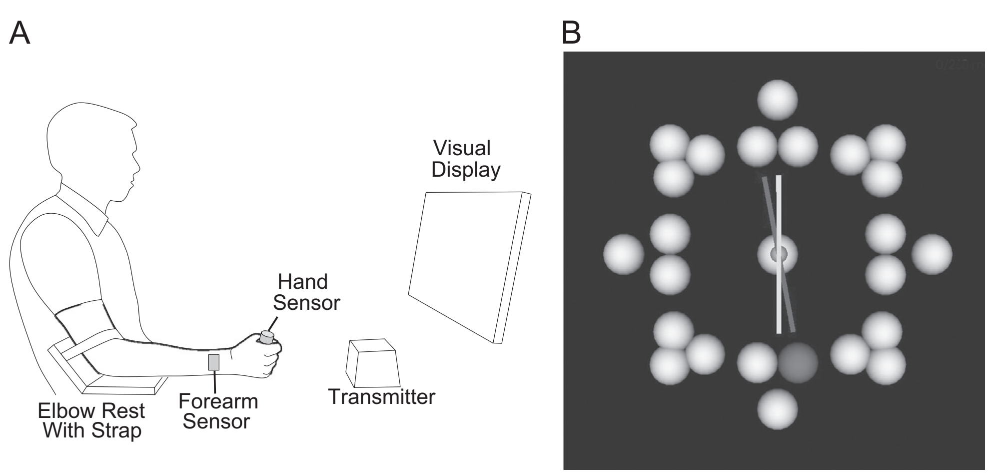

Fig. 1. Experimental setup (A) and visual display (B). The subject was instructed to move the cursor (visible in the center target) to one of the peripheral targets (a target to the bottom right is visibly highlighted) by use of wrist FE and RUD, while simultaneously aligning the crosshairs (which attached to the cursor) to achieve the desired amount of forearm PS. The darker crosshair is the target PS, while the lighter crosshair represents the subject's current PS.

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