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Vector-based forearm rotation moment arms – A sensitivity analysis

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ABSTRACT

All existing moment arm data for muscles of the forearm derive from tendon excursion experiments. Moment arms determined this way are only valid for movement about the same generalised coordinate system as was used during the tendon excursion, which makes their implementation in more complex or realistic joint models problematic. This study used a vector-based method to calculate muscle moment arms in a three dimensional model of forearm rotation. It also evaluated the sensitivity of this method to errors in the input data. There was reasonably close agreement between the moment arms calculated in this study and those published using tendon excursion methods. Six out of eight muscles had moment arms within the range of values reported previously. However, the vector-based method was sensitive to the accuracy of the input data. This sensitivity varied between muscles and input variables. Generally, the calculations were more robust to the point of force application than the muscle lines of action and the joint's axis of rotation. A small change in these variables could produce substantial changes in the calculated moment arms. Consequently, accurate input data is important when using the vector-based method in a joint model.

1. Introduction

Muscle moment arms are a fundamental parameter for modelling joint systems. They directly relate the force a muscle produces to the torque it creates about a joint, and therefore, the movement it will generate. Most muscle moment arms have been determined using the tendon excursion method, which is based on the principle of virtual work [1,2]. If the change in muscle length is infinitesimally small, then that change in length, with respect to the associated change in joint angle, can give the instantaneous moment arm of the muscle through the joint's range of motion. Specifically, a muscle's moment arm is the partial derivative of its length with respect to the joint's angle.

Most commonly, tendon excursion has been performed experimentally using cadaveric specimens [3–5]. This involves rotating a joint through its range of motion and simultaneously measuring the change in a muscle's length. Tendon excursion experiments can also be simulated virtually, typically using a computer model of the joint and associated muscles [6,7]. A significant limitation of this method is that the resulting moment arms are only valid for movement about the same axis (or within the same plane) as was used in the tendon excursion analysis. That is, the generalised coordinate system must be the same. All existing pronosupination moment arms for muscles of the forearm have been determined using the tendon excursion method [4,7–9]. In every case, the radius was rotated over a fixed ulna. Therefore, the published muscle moment arms are only applicable to forearm rotation where the ulna does not move. Furthermore, muscles that attach to the ulna cannot be included in the analysis since the ulna is assumed to be stationary. In reality, the ulna is mobile during functional forearm rotation and its specific movement may be task-dependent [10,11]. If the axis of forearm rotation is task-dependent, a muscle's moment arm will be specific not only to the position of the muscle relative to the joint, but also the precise axis about which the joint is rotating. To account for this, it would be necessary to perform tendon excursion experiments about numerous, functionally meaningful forearm rotation axes. This makes incorporating forearm muscle moment arms into a realistic upper limb biomechanical model problematic.

An alternative method for calculating moment arms uses the classic formulation of a moment, based on the cross product of a position and force vector. This method calculates a muscle's instantaneous moment arm exactly and relative to the precise axis about which the joint is rotating. The vector-based approach has been applied experimentally [12] and a recent study demonstrated its use with a simplified, 2D joint model [13].

Abbreviations: APL, abductor pollicis longus; BB, biceps brachii; BRAR, brachioradialis; ECRL, extensor carpi radialis longus; ECU, extensor carpi ulnaris; FCR, flexor carpi radialis; FCU, flexor carpi ulnaris; MR, magnetic resonance; PT, pronator teres.

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While the mathematics of this method provide an exact moment arm, its practicality for use in a detailed joint model depends on the sensitivity of the calculations to the accuracy of the input data. To that end, the first goal of the present study was to explore the use of this method for calculating moment arms in a more complex, 3D model of forearm rotation. The second goal was to evaluate the sensitivity of the calculations to the input data required by its equations.

2. Methods

2.1. Vector-based muscle moment arms

The cross product of a force vector (**f**) and position vector (**p**) is a vector that represents the moment produced by the force:

$$\boldsymbol{\tau}_{j,m} = \mathbf{p}_{j,m} \times \mathbf{f}_m \tag{1}$$

where j and m are the joint and muscle of interest, respectively. The position vector, **p**, is taken from the centre of rotation to the point of force application. The direction of the moment vector, $\boldsymbol{\tau}$, gives the axis about which the moment is generated and its magnitude gives the magnitude of the moment about that axis. The force vector can be further represented by:

$$\mathbf{f}_m = F_m \hat{\mathbf{f}}_m \tag{2}$$

where the complete force vector is the product of a unit vector, $\hat{\mathbf{f}}$, describing its direction and a scalar, F, describing its magnitude. Combining these two equations gives the following:

$$\boldsymbol{\tau}_{j,m} = F_m \left(\mathbf{p}_{j,m} \times \hat{\mathbf{f}}_m \right) = F_m \mathbf{r}_{j,m} \tag{3}$$

where the moment vector is a product of the scalar force magnitude and a unique vector, **r**, which is orthogonal to both the position and force vector. If the muscle is acting across a ball-and-socket type joint (where rotation can occur about any axis), the direction of **r** (and thereby $\boldsymbol{\tau}$) gives the axis about which the muscle would generate a moment at that joint. The magnitude of **r** gives the muscle's moment arm for rotation about that axis. This is evident if movement is considered within a plane perpendicular to **r**. The system then reduces to the familiar two dimensional form, so that:

$$\left| \boldsymbol{\tau}_{j,m} \right| = F_m \left| \mathbf{r}_{j,m} \right|$$

$$r_{j,m} = \frac{\tau_{j,m}}{F_m} \tag{4}$$

Therefore, it is possible to calculate the instantaneous moment arm, r, for any force vector without making assumptions about the axis of rotation. A muscle's moment arm depends only on its line of pull (the orientation of the force vector and point of force application) and the joint's centre of rotation. Although this is useful for modelling complex joints, it is difficult to compare muscle moment arms calculated this way. Each moment arm is unique to the axis about which the moment is created. It is also problematic when a joint's movement is constrained to occur about a specific axis of rotation, for example at the elbow or knee. In that case, it is necessary to calculate the component of the muscle's moment arm relevant to rotation about the joint's axis of rotation. This can be achieved using the dot product

$$r^a_{j,m} = \mathbf{r}_{j,m} \cdot \hat{\mathbf{a}} = (\mathbf{p}_{j,m} \times \hat{\mathbf{f}}_m) \cdot \hat{\mathbf{a}} \tag{5}$$

where $\hat{\mathbf{a}}$ is a unit vector that represents the orientation of the joint's axis of rotation and $r^a_{j,m}$ is the muscle's moment arm for movement about that axis. In this way, an instantaneous moment arm can be decomposed into a moment arm about any other axis, including axes that are anatomically meaningful. This is particularly useful for modelling biarticular muscles. Once their line of action and point of force application have been defined, their moment arm can be calculated relative to either joint axis. For example, this paper considers the roles of muscles in forearm rotation. However, elbow flexion–extension moment arms can easily be calculated for biarticular muscles, by substituting the elbow's centre of rotation and joint axis into Eq. (5).

2.2. Determining forearm muscle moment arms

To determine muscle moment arms using the method described above, it is necessary to know the muscle's point of force application and to have a vector representing its direction of pull. To that end, a detailed, magnetic resonance (MR) imaging-based model of the forearm was developed. The right arm of a 27 year old, healthy, male participant (72 kg, 174 cm) was scanned using a 3T Siemens Skyra MR imaging scanner (Siemens Medical Systems, Erlangen, Germany) and two body receiver coils. The position of the subject's upper limb was controlled using a specially designed, MR compatible jig. Their forearm was held horizontal and in the neutral position. Their humerus was positioned approximately 45° above horizontal so that their elbow angle was 135°. The images were T1-weighted axial slices (TR = 5.89 ms, TW = 2.45 ms), with an in-plane resolution of 0.5625 mm and a slice thickness of 3 mm.

Eight forearm muscles were included in the analysis: abductor pollicis longus (APL), biceps brachii (BB), brachioradialis (BRAR), extensor carpi radialis longus (ECRL), extensor carpi ulnaris (ECU), flexor carpi radialis (FCR), flexor carpi ulnaris (FCU) and pronator teres (PT). These muscles were chosen to represent a variety of attachment sites, lines of action and distances from the axis of forearm rotation. Muscles were segmented manually from the MR images using in-house software, cmiss (http://www.cmiss.org). All muscles visible in the MR images were segmented to ensure muscle boundaries were consistent and as accurate as possible. Segmentation was performed in conjunction with anatomy texts and, where necessary, the consultation of a clinician. For the purposes of visualisation and to make it easier to identify the axis of rotation, the humerus, radius and ulna bones were also segmented. The resulting data clouds were used to construct parameterised, geometric meshes of the three bones and eight muscles.

The standard, anatomical axis of forearm rotation was used in this analysis – an axis that passes through the ulnar head distally and the radial head proximally [11,14]. The centre of rotation was chosen as the point on that axis where it passed the distal radioulnar joint. It can be shown that the location of the centre of rotation will not affect the calculated moment arms provided that it lies on the axis of rotation. A curve representing the three dimensional path of the muscle was constructed through the point at the centre of each row of elements, as depicted in Fig. 1. Cubic Hermitian interpolation was used to ensure the muscle path was smooth. The muscle's line of action ($\hat{\mathbf{f}}$) was determined as the tangent to its muscle path at the point of its insertion onto the radius. The point of insertion specified the point of force application and was used to determine the muscle's position vector (**p**). For those muscles that attached to the hand (APL, ECRL, ECU, FCR, and FCU), the first point at which their tendons became "free" after passing the distal radioulnar joint was taken as their point of force application. Moment arms for the eight muscles were calculated using Eq. (5).

2.3. Sensitivity analysis

The subsequent analysis evaluated the sensitivity of the calculated moment arms to errors in each of the three input variables. These variable were:

- **p** – the position vector, calculated from the centre of rotation to the muscle's point of force application.

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