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TECHNICAL NOTE

A PARAMETRIC MODEL OF MUSCLE MOMENT ARM AS A FUNCTION OF JOINT ANGLE: APPLICATION TO THE DORSIFLEXOR MUSCLE GROUP IN MICE

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Abstract—A parametric model was developed to describe the relationship between muscle moment arm and joint angle. The model was applied to the dorsiflexor muscle group in mice, for which the moment arm was determined as a function of ankle angle. The moment arm was calculated from the torque measured about the ankle upon application of a known force along the line of action of the dorsiflexor muscle group. The dependence of the dorsiflexor moment arm on ankle angle was modeled as $\mathbf{r} = \mathbf{R}\sin(\mathbf{a} + \Delta)$, where $\mathbf{r}$ is the moment arm calculated from the measured torque and $\mathbf{a}$ is the joint angle. A least-squares curve fit yielded values for $\mathbf{R}$, the maximum moment arm, and Δ, the angle at which the maximum moment arm occurs as offset from 90°. Parametric models were developed for two strains of mice, and no differences were found between the moment arms determined for each strain. Values for the maximum moment arm, $\mathbf{R}$, for the two different strains were 0.99 and 1.14 mm, in agreement with the limited data available from the literature. While in some cases moment arm data may be better fitted by a polynomial, use of the parametric model provides a moment arm relationship with meaningful anatomical constants, allowing for the direct comparison of moment arm characteristics between different strains and species. Copyright © 1996 Elsevier Science Ltd.

Keywords: Biomechanics; Biological models; Moment arm; Ankle; Mice.

INTRODUCTION

The muscle moment arm, defined as the perpendicular distance from the line of action of a muscle to the joint center of rotation, transforms the linear movement of muscle into rotation about a joint. The externally measurable quantity of torque results from the cross-product of the moment arm and the force developed by the muscle. In order to determine the actual force generated as muscles contract *in vivo*, the moment arm must be characterized as it varies throughout the range of motion. A number of methods for determining muscle moment arms have been reported (An *et al.*, 1984). Moment arms have been measured from serial sections (An *et al.*, 1981; Jensen and Davy, 1975), and from scans produced by computed tomography (Németh and Ohlsén, 1985, 1986) and magnetic resonance imaging (Rugg *et al.*, 1990; Spoor and van Leeuwen, 1992). Alternatively, moment arms have been derived from expressions relating tendon excursion (An *et al.*, 1983; Spoor and van Leeuwen, 1992) or muscle length (Visser *et al.*, 1990) to joint angle.

In human beings, muscle moment arms have been reported at various joints, including the hip (Németh and Ohlsén, 1985), knee (Grood *et al.*, 1984; Spoor and van Leeuwen, 1992), ankle (Rugg *et al.*, 1990), and elbow (An *et al.*, 1981; Murray *et al.*, 1995). Although the angular dependence of moment arms has been determined using polynomial curve fits (Murray *et al.*, 1995) or other fitting methods (An *et al.*, 1981), the coefficients of these equations generally do not have anatomical significance.

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Our objective was to develop a parametric model, incorporating useful anatomical constants, to describe the relationship between the moment arm and joint angle. In the present study, we investigated the moment arm of the dorsiflexor muscle group in mice as a function of ankle joint angle. We utilized a more direct method of moment arm determination (Draganich *et al.*, 1987; Grood *et al.*, 1984) in which a torque was produced about the ankle by the application of a known force along the line of action of the dorsiflexor muscle group. The parametric model was applied to moment arm data obtained from two different strains of mice to determine if the model parameters varied.

MATERIALS AND METHODS

Data were collected from mice of two different strains, ranging between 6 and 8 months of age. The moment arm as a function of ankle angle was determined in four female B6D2F1 mice (26.7 ± 1.1 g) and three female and two male HET3 mice (28.1 ± 1.9 g). Since one of our objectives was to determine a possible dependence of the moment arm relationship on the strain rather than the gender of the mice, the female and male HET3 mice were considered as one group. All experimental procedures were conducted in accordance with the National Institutes of Health Guide for the Care and Use of Laboratory Animals.

Mice were euthanized with an overdose of pentobarbital sodium and both hindlimbs were severed at the distal femur. The dorsiflexor muscle group was separated from the tibia at the origin and a loop of suture was secured around the muscle group near the proximal end. The foot was strapped securely in a shoe fixture on a testing apparatus similar to that described by Ashton-Miller *et al.* (1992). The hindlimb was secured with a pin near the tibial plateau in order to fix the orientation of the tibia during the ankle joint rotations (Fig. 1). The shoe fixture was

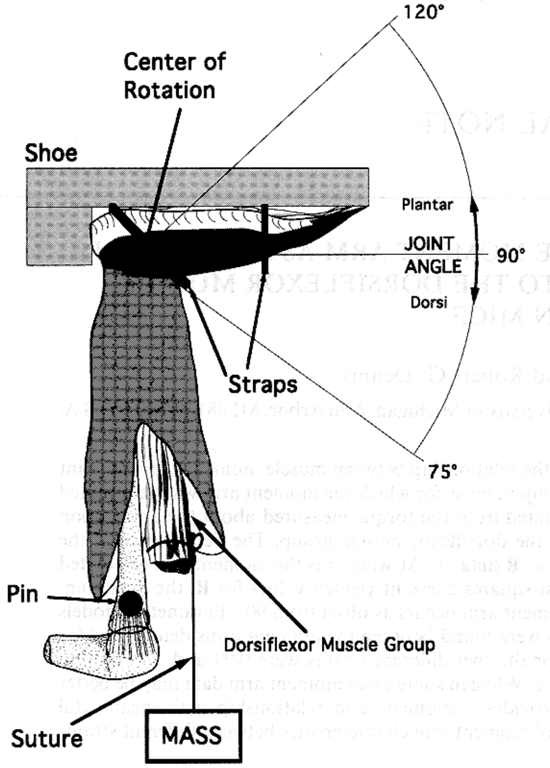

Fig. 1. Schematic representation of the experimental setup. A severed mouse hindlimb is shown as it is attached to the apparatus. The foot is strapped into a shoe fixture such that the ankle and the axis of rotation are coaxial. The hindlimb is secured with a pin at the tibial plateau, and calibrated weights are suspended from the dorsiflexor muscle group. Ankle position is controlled by a servomotor.

attached to a torque transducer (model QWFK-8M, Sensotec, Columbus, OH) such that the center of rotation of the ankle joint was aligned visually with the axis of the torque transducer. With the hindlimb fixed in position, the center of rotation was verified by moving the ankle throughout its range of motion and ensuring that the foot did not translate.

To allow for angular positioning of the ankle joint, the torque transducer was mounted to the shaft of a custom-built servomotor. The axis of rotation of the transducer was horizontal, and the hindlimb was positioned such that the line of action of the dorsiflexor group was vertical with the proximal end pointing downward (Fig. 1). This configuration allowed calibrated weights to be suspended from the suture loop to generate known forces along the line of action of the muscle group. The proximal end of the muscle group was placed immediately adjacent to the tibial plateau, so as to best replicate the line of action as it occurs *in vivo*. Distally, the tendons of the dorsiflexor muscle group are held close to the ankle joint by retinacula (Greene, 1963; Ashton-Miller *et al.*, 1992), preventing displacement which could alter the line of action. These retinacula also prevent large variations in the moment arms of the individual dorsiflexor muscles, allowing the moment arm–joint angle relationship developed for the entire dorsiflexor group to be representative of the relationships for the individual muscles as well.

The servomotor was rotated in 5–10° increments throughout the range of motion, beginning at the 90° neutral position and rotating up to 15° of dorsiflexion (75° ankle position) and 30° of plantarflexion (120° ankle position). A Macintosh Quadra 700 computer (Apple Computer, Cupertino, CA) utilizing LabVIEW software (National Instruments, Austin, TX) controlled the servomotor and recorded the torque measurements. At each ankle position, torque was first measured without a weight suspended from the suture loop, in order to account for torque production due to the weight of the hindlimb and shoe fixture. Subsequently, the torque was recorded with 50 and 100 g weights hanging from the suture loop, and from these measurements the baseline torque was subtracted. The moment arm of the dorsiflexor muscle group was then calculated by dividing the resultant torque by the known force due to the hanging weight.

The dependence of the dorsiflexor moment arm on ankle angle was modeled as $\mathbf{r} = \mathbf{R}\sin(\mathbf{a} + \Delta)$. In this parametric equation, **r** represents the moment arm (mm) and **a** is the joint angle (degrees). A least-squares curve fit yielded values for **R**, the maximum moment arm, and Δ, the offset angle of the maximum moment arm from the neutral position (90°). A repeated measures analysis of variance (ANOVA) was used to determine statistical significance between the moment arms calculated using the 50 and 100 g weights and between the moment arms calculated for the B6D2F1 and HET3 strains. The level of significance was set a priori at $\alpha = 0.05$.

RESULTS

The moment arm of the dorsiflexor muscle group was determined for the B6D2F1 (Fig. 2A) and HET3 (Fig. 2B) strains at

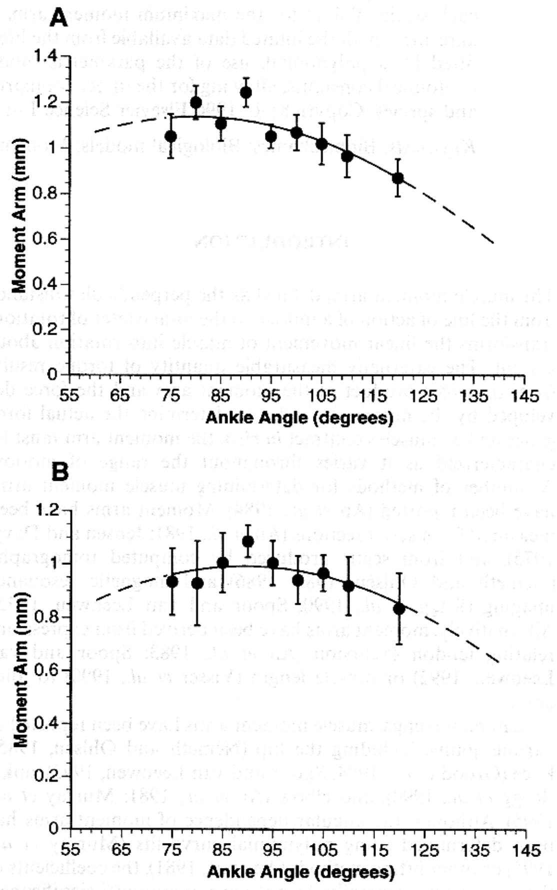

Fig. 2. Moment arm (**r**) of the dorsiflexor muscle group as a function of ankle angle (**a**) in (*A*) B6D2F1 mice and (*B*) HET3 mice. Data are shown as means $\pm$ SE. The solid lines represent the least-squares fit of the data given by the parametric model $\mathbf{r} = \mathbf{R}\sin(\mathbf{a} + \Delta)$, where **R** is the maximum moment arm and Δ is the offset angle of the maximum moment arm from 90°. The dashed lines represent an extrapolation of the model to angles outside the range tested.

Table 1. Model parameters determined for each strain of mice

Strain	Maximum moment arm **R** (mm)	Offset angle Δ	Peak angle $90° - \Delta$
B6D2F1	1.14	10.1°	79.9°
HET3	0.99	0.6°	89.4°

ankle angles ranging from 75 to 120°. No difference was found between the moment arm values obtained using the 50 and 100 g weights, and these data were subsequently averaged for each ankle angle. The data reported represent these pooled values.

The data set for each strain was modeled parametrically, with **R** and Δ determined by the method of least squares (Table 1). A positive value of Δ indicates dorsiflexion with respect to the 90° neutral position, while a negative value indicates plantar flexion. The peak angle, defined as the ankle angle at which the maximum moment arm occurred, was calculated as $90° - \Delta$. The sum of the squared error between the experimental points and the fitted model was 0.0286 for the B6D2F1 strain, whereas for the HET3 strain the squared error was 0.0143.

No significant difference was found between the moment arms of the B6D2F1 and HET3 strains throughout the range of motion studied. Individual measurements of moment arm values ranged from 0.59 to 1.52 mm for the B6D2F1 strain and from 0.37 to 1.49 mm for the HET3 strain.

DISCUSSION

The parametric model developed for the muscle moment arm as a function of joint angle is a valuable alternative to equations obtained from polynomial curve fits. Although in some cases a polynomial may provide a better fit to the experimental data, the parameters of the model equation, **R** and Δ, have anatomical significance generally not obtained from polynomial coefficients. Furthermore, the model parameters can be used for the direct comparison of experimental attributes between different subjects. Since the relationship between muscle moment arm and joint angle resembles a sine function for certain studies of the knee (Grood *et al.*, 1984; Spoor and van Leeuwen, 1992), hip (Németh and Ohlsén, 1985), and elbow (Murray *et al.*, 1995), a parametric model similar to the one described here may be applicable elsewhere.

Despite the advantages described, the parametric model proposed in the present study should be implemented with caution. The sine function is only appropriate in cases where the joint angle does not approach 90° offsets from the neutral position. The model would predict a zero moment arm at these positions, which clearly is not anatomically possible due to the finite radius of the joint capsule. If the limitation on the range of motion of the joint is satisfied, the parametric model may be applied if the moment arm data appear to follow a sinusoid over the range of interest.

Previous studies have utilized several types of methods for determining muscle moment arms (An *et al.*, 1984). For applications involving human beings, the noninvasive nature of techniques such as computed tomography (Németh and Ohlsén, 1985, 1986) and magnetic resonance imaging (Rugg *et al.*, 1990; Spoor and van Leeuwen, 1992) is attractive. However, the line of action of muscles is difficult to identify with these methods, and Spoor and van Leeuwen (1992) concluded that moment arms derived indirectly as a function of tendon excursion may be more accurate. Theoretically, the method employed in the present study should allow for the most precise determination since we calculate the moment arm directly from the applied load (An *et al.*, 1984). The major constraint involved with our method is that the torque introduced by static friction from surrounding tissues is assumed to be negligible since the force observed at the torque transducer is assumed to be due entirely to be suspended weight.

Two additional notations are necessary in reference to the method of moment arm determination. First, although the center of rotation of the ankle joint in human beings is not stationary (Sammarco *et al.*, 1973), we assumed that the center of rotation of the ankle was fixed and aligned coaxially with the axis of the torque transducer. In mice, experimental evidence suggests that the ankle joint is a hinge joint (Ashton-Miller *et al.*, 1992), so that the assumption of a fixed center of rotation in the present study is reasonable. Second, the moment arm may depend not only on the joint angle in the sagittal plane, but also on the position of the joint in the other axes (Young *et al.*, 1993). Although we took great care to position the hindlimb consistently, variations in abduction/adduction and inversion/eversion represent a potential source of error.

In the present study, the model predicts moment arm values at 90° of 1.12 and 0.99 mm for the B6D2F1 and HET3 strains, respectively. These values correspond with the moment arms of individual dorsiflexor muscles measured from serial cross-sections taken from a 33 g mouse with its ankle fixed at 90° (Ashton-Miller *et al.*, 1992). Unfortunately, no other data exist with which we can verify our moment arm values throughout the range of motion of the ankle joint. Unlike the dorsiflexor muscles, individual muscles spanning the same joint may show very different moment arm behaviors (An *et al.*, 1981; Murray *et al.*, 1995; Spoor and van Leeuwen, 1992). Although we have determined moment arm values for the entire dorsiflexor muscle group, the proposed model and method of measurement would work equally well for determining the moment arms of individual muscles.

In conclusion, we have developed a parametric model to describe the relationship between moment arm and joint angle. We applied the model to the dorsiflexor muscle group in two strains of mice, and found that the moment arm–ankle angle relationships determined for the two strains did not differ. The model may be applicable in other joint systems, provided constraints on the range of motion studied and general shape of the data are considered. While in some cases moment arm data may be better fitted by a polynomial, use of the parametric model provides a moment arm relationship with meaningful anatomical constants, allowing for direct comparison of moment arm characteristics between different strains and species.

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