*Archives Italiennes de Biologie, 140: 237-245, 2002.*

# CAPTURING THE FRAME OF REFERENCE OF SHOULDER MUSCLE FORCES

C.A. BUNEO[+], J.F. SOECHTING AND M. FLANDERS[*]

*Department of Neuroscience, University of Minnesota, 321 Church Street, Minneapolis, MN 55455*

## INTRODUCTION

Terzuolo and colleagues asked subjects to draw circles in the air, in various vertical planes (22). They found that if the coordinate system for joint angles is properly chosen, there is a simple mapping between the rotations of the elbow and shoulder and the movement of the hand in space. They noted, however, that the mapping between joint torque and hand movement is *not* simple, and showed that it is not clear whether shoulder joint torques should be expressed in body-centered or arm-centered coordinates. A decade later, we measured shoulder torques and demonstrated that the muscles act in a frame of reference that is intermediate to reference frames fixed to the body and fixed to the humerus (5). As reported here, we then attempted to construct a model that would capture the geometry of shoulder muscle moments.

The direction and amplitude of a muscular moment of force depends on the limb posture (cf. 3, 29). Models of the relation between muscle moment and limb posture have been based on anatomical measurements via radiography (1, 13), computed tomography (16) or magnetic resonance imaging (21, 23). Anatomical parameters can also be estimated by direct digitization (27) or serial cross-sectioning (2, 10) of cadaver musculature. From such measurements, a geometric model of each muscle is typically developed, representing the muscle by its line of action (either straight or curved). Muscle moments are then computed directly from the moment arms of the model or by using the principle of virtual work (12). For shoulder muscles (the object of our study), several investigators have used this type of approach to describe muscular action (e.g. 4, 7, 19, 24, 25, 26, 27).

Anatomically based muscle models necessarily involve major approximations. Muscles that curve around a joint are generally represented as having a straight line of action, from an estimated "effective" origin to an estimated "effective" insertion. Thus, there is a real need to validate such models by comparing their predictions with the actual moments produced by the muscles. We have approached this problem by electrically stimulating the major shoulder muscles under isometric conditions, with the arm in a wide range of postures, and measuring the resulting torques (5).

[*]*Address for correspondence.* - Dr. Martha Flanders, Department of Neuroscience, 6-145 Jackson Hall, University of Minnesota, 321 Church Street S.E., Minneapolis, MN 55455. Tel. (612) 624 6601, Fax: (612) 626 5009, E-mail: fland001@umn.edu

[+]Current Address: Division of Biology, Caltech, Pasadena, CA 91125

## METHODS

*Experimental procedures.*

A complete account of the experimental procedures employed is provided elsewhere (5). Data were obtained from three adult human subjects, who gave their informed consent prior to their participation in the procedures which were approved by the Institutional Review Board of the University of Minnesota. The following shoulder muscles of the right arm were examined: anterior deltoid, medial deltoid, posterior deltoid, latissimus dorsi, clavicular head of pectoralis major and the upper portion of the sternocostal head of pectoralis major.

The subjects sat in a modified dental chair that was coupled to a rigid stereotaxic frame. A six-degree-of freedom force-torque sensor ($JR^3$ Inc., Woodland, CA) was coupled to the frame at one end and to the elbow of an upper-arm orthosis at the other end, the axes of the sensor being aligned with the axes of the humerus. Muscle contractions were obtained with a dual-channel neuromuscular electrical stimulation unit (Respond Select, Empi Inc., St. Paul, MN) using bipolar, circular (3 cm diameter) surface electrodes. The unit was preprogrammed to provide a trapezoidal modulation of the amplitude of current pulses: a 1 s ramp up to peak current, followed by a 1 s hold, followed by a 0.5 s ramp down to 0 current. In each experiment, up to 29 postures of the upper arm were examined. The elbow angle was constant (90°) and the position of the scapula was not constrained.

*Data Analysis.*

Muscle torques were computed from the forces and torques recorded at the transducer, in accord with the demands of static equilibrium. They were defined in a reference frame fixed to the humerus (Fig. 1): the $y$-axis (internal rotation) along the long axis of the humerus, the $z$-axis (flexion) perpendicular to the plane of the arm (upper arm and forearm), and the $x$-axis (adduction) perpendicular to the other two. With the upper arm vertical, the positive $x$ axis was anterior, positive $y$ superior and positive $z$ lateral. The direction of the three-dimensional shoulder torque vector (**M**) was defined by two angles: $\alpha$ and $\beta$. Alpha ($\alpha$) is the angle that the projection of the torque vector onto the **x-z** plane makes with the -**x** axis and beta ($\beta$) is the angle that the torque vector makes with the **x-z** plane.

$$\tan(\alpha) = (-\mathbf{M}_z/-\mathbf{M}_x) \qquad (1)$$
$$\tan(\beta) = (\mathbf{M}_y/\mathbf{M}_{xz})\ (\mathbf{M}_{xz} = \sqrt{}\,(\mathbf{M}_x + \mathbf{M}_z))$$

Arm posture was derived from the recorded location of spherical reflective markers (placed on the orthosis at the shoulder, elbow and wrist), using a video-based, three-dimensional motion analysis system (VP110, Motion Analysis Corp.). Upper arm azimuth ($\eta$), elevation ($\Theta$) and humeral rotation ($\zeta$) were computed from the measured locations of the elbow and wrist relative to the shoulder.

*Multiple Regression Analysis.*

The postural dependence of muscle torque direction (defined by $\alpha$ and $\beta$) was examined quantitatively by means of multiple regression analysis. Each angle was fit to a 4-term model containing linear functions of $\zeta$, $\Theta$, and $\eta$, as well as a 20-term model containing linear, quadratic and cubic polynomial terms. For example, for the linear model of $\beta$

$$\beta = a_0 + a_1\zeta + a_2\Theta + a_3\eta + \varepsilon \qquad (2)$$

where $a_0$ - $a_3$ represent the coefficients of the various terms in the model, and $\varepsilon$ represents the error. For all models, the coefficients $a_i$ were determined by singular value decomposition (20). We also computed similar models including only those terms which provided a significant contribution to the overall fit by means of a stepwise regression procedure, where terms are iteratively added to the model and each term is tested for its contribution to the overall fit by means of a partial F-test (8).

*Anatomical Modeling.*

To relate the results of the multiple regression analysis to the anatomical models of the musculoskeletal system we initially used SIMM (MusculoGraphics, Inc., Evanston, IL). In SIMM, the geometry of a muscle and its tendon is defined by a series of points connected by line segments. Two of the points represent the muscle's origin and insertion. Any number of additional via points, fixed with respect to either the distal or proximal joint segments, can then be specified to more completely define the muscle path. We assessed whether models consisting of an origin (O), an insertion (I), and two via points (an effective origin (Vo) and an effective insertion (Vi)) could produce torques in directions that reasonably approximated those predicted by our multiple regression analysis.

Muscle origins and insertions were taken from the SIMM model of Yamaguchi et al. (28). The initial locations of our via points (Vo and Vi) were obtained interactively in SIMM by manually moving the via points to approximate the experimental data for a single posture ($\eta = \Theta = \zeta = 0°$). In the line-segment muscle models we developed, O and Vo were assumed to be fixed to the scapula and I and Vi to the humerus. As a result, only segment Vo-Vi changed length as the humerus rotated with respect to the scapula. From the principle of virtual work [6,12], the components of muscle torque ($\mathbf{Ms}_x$, $\mathbf{Ms}_y$, and $\mathbf{Ms}_z$) are related to the location of the via points by:

$$
\begin{aligned}
\mathbf{Ms}_x &\approx \mathbf{Vo}_y(\mathbf{Vo}_z-\mathbf{Vi}_z) - \mathbf{Vo}_z(\mathbf{Vo}_y-\mathbf{Vi}_y)\\
\mathbf{Ms}_y &\approx \mathbf{Vo}_z(\mathbf{Vo}_x-\mathbf{Vi}_x) - \mathbf{Vo}_x(\mathbf{Vo}_z-\mathbf{Vi}_z)\\
\mathbf{Ms}_z &\approx \mathbf{Vo}_x(\mathbf{Vo}_y-\mathbf{Vi}_y) - \mathbf{Vo}_y(\mathbf{Vo}_x-\mathbf{Vi}_x)
\end{aligned}
\tag{3}
$$

To compare the predictions of the line-segment models to the predictions of our regression model we found the locations of Vo and Vi for each muscle that minimized the following error function:

$$
\mathrm{E} = \sum_{i=1}^{N} (\psi)^2 \tag{4}
$$

where $\psi$ is the angle between vectors $\mathbf{Mr}$ and $\mathbf{Ms}$ (representing the muscle torque axes at the shoulder predicted by the regression models and line-segment models, respectively), at each of $N = 28$ postures of the upper arm. For these postures, $\eta$ ranged from -15° to -75°, $\Theta$ ranged from 15° to 75°, and $\zeta$ ranged from -15° to 75°. The optimal locations of Vo and Vi were determined using the simplex method (15, 20).

We also performed a sensitivity analysis on the locations of Vo and Vi determined by the optimization. For this analysis, either Vo or Vi was displaced 1 cm in each of 18 directions. For each displacement we calculated the error as defined in Eqn. 4, subtracted the corresponding error for no displacement, then fit the data for all displacements to the equation for an ellipsoid.

## RESULTS

*Modeling of dependence of muscle torque direction on posture.*

As demonstrated previously (5), physiologically defined muscle torque directions depended in a simple, systematic manner on the posture of the arm. In fact, when muscle torque directions were defined by the angles $\alpha$ and $\beta$ (see Eqn. 1), these two angles were linearly related to the angles defining the posture of the humerus ($\eta$, $\theta$ and $\zeta$). The nonlinear models generally gave only a small improvement in the values of the correlation coefficients. Most of the muscles showed a similar degree of dependence on azimuth and humeral rotation, the exception being MD. Trends with $\Theta$ were more variable. This regression procedure provided a quantitative record of muscle moment directions that could be used to validate anatomical models.

*Relating physiological and anatomical models.*

Simple line-segment models were able to approximate the muscle moment directions discussed above. Our estimates of the origins, insertions and via points for each of the six muscles are presented in Table 1, where the coordinates of the origins (O) and effective origins (Vo) are expressed in a frame of reference that is fixed to the scapula and the insertions (I) and effective insertions (Vi) are expressed in a frame of reference that is fixed to the humerus. The origin of both coordinate systems is located at the approximate center of rotation of the glenohumeral joint.

Plots of the musculoskeletal geometry obtained by the optimization procedure are depicted in Figures 1 and 2. In the plot of Medial Deltoid (Fig. 1) the bones and muscles are viewed from an oblique angle with the upper arm positioned at $\eta = \Theta = \zeta = 0°$: the clavicle runs parallel to the negative z-axis (which points obliquely into the page) and the forearm runs parallel to the positive x-axis (which points obliquely out of the page). Each line-segment model (Figs. 1 and 2) is viewed from the same perspective but at a variable magnification.

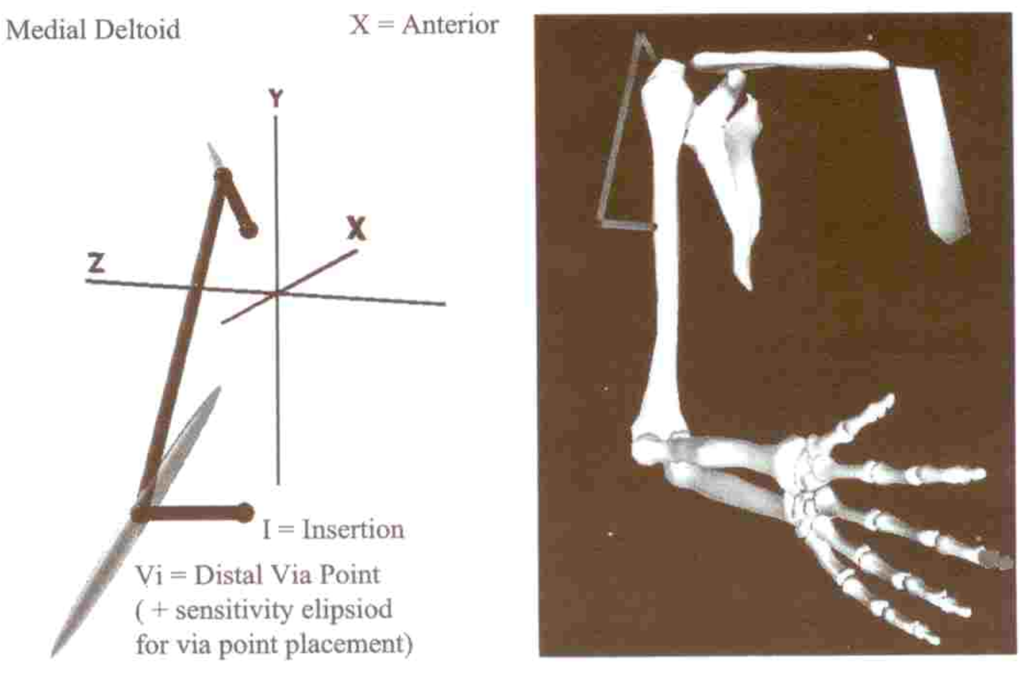


Fig. 1. - *Line-segment model of medial deltoid.*
On the right is a perspective plot of the line-segment model superimposed on a model of the skeleton (upper arm vertical, forearm horizontal). On the left, a plot of the same line segments is shown at higher magnification. Sensitivity ellipsoids are superimposed on the via points in the plot on the left. The long axis of each ellipsoid indicates the direction along which predicted torque direction was insensitive to via point location. The plot on the right was generated using SIMM (MusculoGraphics, Inc.).

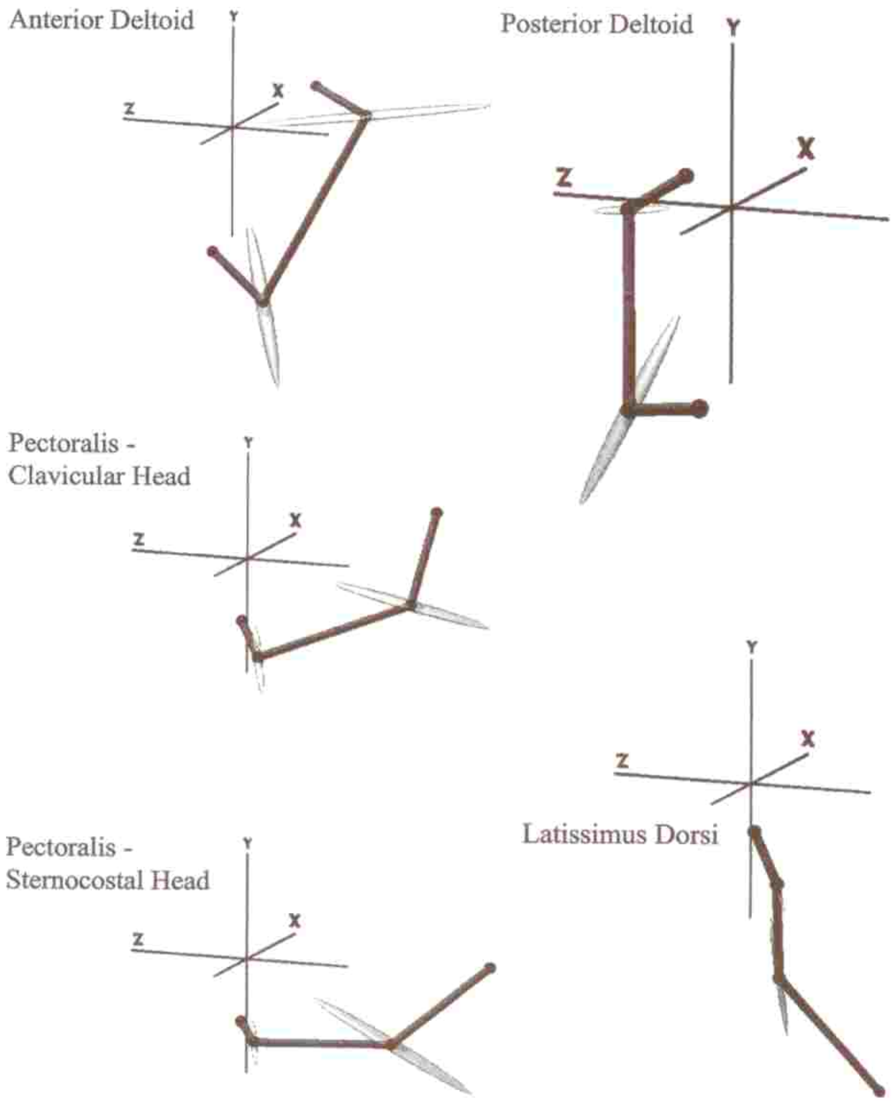


Fig. 2. - *Line-segment models of anterior deltoid, posterior deltoid, latissimus dorsi, and the clavicular and sternocostal heads of pectoralis major.*
The format is the same as Figure 1.

All of the line-segment models grossly resemble the true muscle paths (14). This is despite the unconstrained nature of the optimization, which could have placed the via points anywhere in three-dimensional space. However, because we used only four points to approximate each path, the line segments have a jagged appearance.

A sensitivity analysis on the locations of the via points in our line-segment mod-

Table 1. - *Three-dimensional coordinates (in cm) of the points defining muscle geometries in SIMM.* Also shown are the RMS values (in degrees) of the angular differences between the torque direction vectors predicted by the SIMM model and the regression model.

| Muscle | | O | Vo | Vi | I | RMS |
|---|---|---|---|---|---|---|
| AD | x | 2.4 | 8.0 | 2.6 | -0.1 | 10.2 |
| | y | 4.1 | 0.2 | -15.4 | -11.4 | |
| | z | -7.5 | -9.1 | -1.8 | 1.8 | |
| MD | x | -0.2 | -0.4 | 0.8 | -0.1 | 11.1 |
| | y | 3.4 | 6.3 | -11.3 | -11.4 | |
| | z | 1.5 | 2.9 | 7.2 | 1.8 | |
| PD | x | -3.7 | -6.1 | -4.2 | -0.1 | 10.8 |
| | y | 2.6 | 0.7 | -11.6 | -11.4 | |
| | z | 1.6 | 4.5 | 4.6 | 1.8 | |
| LaD | x | -10.1 | -3.5 | 1.0 | 1.0 | 4.7 |
| | y | -25.3 | -14.6 | -7.5 | -3.8 | |
| | z | -15.8 | -3.6 | -1.6 | 0.1 | |
| CPec | x | 6.8 | 5.8 | 2.3 | 0.6 | 10.4 |
| | y | 4.0 | -4.3 | -8.8 | -5.7 | |
| | z | -15.0 | -12.5 | -0.1 | 0.7 | |
| SPec | x | 6.9 | 4.7 | 1.4 | 0.6 | 11.3 |
| | y | -0.6 | -7.6 | -7.5 | -5.7 | |
| | z | -20.2 | -11.2 | -0.2 | 0.7 | |

els revealed that the predicted torque directions were not uniformly sensitive to a displacement of the via points by 1 cm in each of 18 directions. A sensitivity ellipsoid is shown on each via point in Figures 1 and 2. In each case the directions of displacement associated with the *smallest* errors in torque direction correspond to the *largest* dimensions of an ellipsoid. The orientations of the long axis are reasonable from a mechanical point of view: they point toward the origin of the scapulo-humeral coordinate system, i.e. the center of rotation of the glenohumeral joint. Moving the via points along these directions affects torque direction minimally because moving the line of action toward the center of joint rotation changes only the length of the moment arm. This would influence the magnitude of the torque and but not its direction.

To provide an indication of how well the line-segment models presented in Figs. 1 and 2 accounted for the experimental data, we present in the rightmost column of Table 1 the RMS errors between the torque direction vectors predicted by these line-segment models and the vectors predicted by our regression models. For all muscles these values were approximately equal to or less than allowable experimental error in torque direction 10° (5). It is noteworthy that the muscle with the smallest RMS deviations was LaD, which we have represented using only the middle of the three paths used by Yamaguchi and colleagues (28). This suggests that even for muscles with large attachment sites, the postural dependence of muscle action can be summarized using a single muscle path with well-defined via points.

## DISCUSSION

In this paper we demonstrated that simple anatomical models of muscle, when combined with physiologically obtained data on muscle torque directions, can reasonably approximate the mechanical actions of six human arm muscles across a large range of arm postures. In this Discussion we will first focus on general issues related to modeling the geometrical properties of muscle and then on ways in which these methods could be improved.

In musculoskeletal modeling, how one chooses to represent the path of the muscle is critical (30). Muscle lines of action are typically modeled as either straight lines or curved paths, depending on the muscle and/or the methodology used (reviewed in 18). In the present study, none of the optimal line-segment models approximated a straight line from origin to insertion. The suggestion that muscles can be modeled adequately with a single line segment from origin to insertion is usually based on anatomical data obtained within a single posture (e.g., see 27). The results of our modeling efforts, which are based on physiological data, indicate that in order to effectively model the mechanical actions of six shoulder muscles across a range of arm postures, the geometry must approximate a curve in space, i.e., a series of straight line segments oriented at some angle to each other.

In general, the line-segment models arrived at by our optimization were both physiologically accurate and anatomically plausible. This does not mean that these models cannot be improved or that the methods used to determine them can accurately model all muscles. With regard to the anatomical realism of the models, our sensitivity analysis has already revealed some ways in which the present models may be modified to make them appear more realistic. Placing additional points in the muscle path could also lead to physiologically accurate models that were also more anatomically realistic. Another way to improve the existing models would be to incorporate additional anatomical data into the optimization procedures. For example, anatomical data regarding the length coordinate of each muscle's moment arm could be used to place constraints on the distance of the via points from the center of rotation of the glenohumeral joint.

In some cases, improving our models may require modifying the way they are defined. In the present study, muscle paths were defined as a series of points that were fixed with respect to either the distal or proximal segments of the glenohumeral joint. These models were sufficient to approximate the mechanical actions of all six human arm muscles examined in this study. However, for other muscles it may prove necessary to permit the via points to move within their respective frames of reference with changes in joint angle.

## SUMMARY AND CONCLUSION

We have adjusted and validated models of the lines of action of six human shoulder muscles. Compared to other models of the shoulder mechanism (e.g., 9, 11, 17,

24) ours is greatly simplified in that the scapula and its many muscles are largely neglected, and the action of each of six broad muscles is summarized by a single line segment. The close correspondence between measured and predicted moment direction over a wide range of postures suggests that this latter simplification was reasonable. We found that assignment of two via points (one fixed to the origin and one fixed to the insertion) was adequate to represent the measured actions, and our sensitivity analysis highlights the importance of via point placement. Because our model predicts the action of each muscle over a very large range of arm postures, it should be useful for future investigations of the control of muscle forces.

*Acknowledgements.* -This work was supported by R01 NS27484 from the National Institutes of Health. The authors thank Dr. William Durfee for advice.

## REFERENCES

1. An, K.N., Chao, E.Y., Cooney, W.P. and Linscheid, R.L. Normative model of human hand for biomechanical analysis. *J. Biomech.,* **12**: 775-788, 1979.
2. An, K.N., Hui, F.C., Morrey, B.F., Linscheid, R.L. and Chao, E.Y. Muscles across the elbow joint: A biomechanical analysis. *J. Biomech.,* **14**: 659-669, 1981.
3. Basmajian, J.V. and De Luca, C.J. *Muscles alive. Their functions revealed by electromyography.* Baltimore, MD. Williams and Wilkins, 1985.
4. Bassett, R.W., Browne, A.O., Morrey, B.F. and An, K.N. Glenohumeral muscle force and moment mechanics in a position of shoulder instability. *J. Biomech.,* **23**: 405-415, 1990.
5. Buneo, C.A., Soechting, J.F. and Flanders, M. Postural dependence of muscle actions: Implications for neural control. *J. Neurosci.,* **17**: 2128-2142, 1997.
6. Delp, S.L. and Loan, J.P. A graphics-based software system to develop and analyze models of musculoskeletal structures. *Comput. Biol. Med.,* **25**: 21-34, 1995.
7. De Luca, C.J. and Forrest, W.J. Force analysis of individual muscles acting simultaneously on the shoulder joint during isometric abduction. *J. Biomech.,* **6**: 385-393, 1973.
8. Draper, N.R. and Smith, H. *Applied Regression Analysis.* New York, John Wiley, 1981.
9. Högfors, C., Sigholm, G. and Herberts, P. Biomechanical model of the human shoulder – I. Elements. *J. Biomech.,* **20**: 57-166, 1987.
10. Jensen, R.H. and Davy, D.T. An investigation of the muscle lines of action about the hip: A centroid line approach versus the straight line approach. *J. Biomech.,* **8**: 103-110, 1975.
11. Johnson, G.R., Spalding, D., Nowitzke, A. and Bogduk, N. Modeling the muscles of the scapula morphometric and coordinate data and functional implications. *J. Biomech.,* **29**: 1039-1051, 1996.
12. Kane, T.R. and Levinson D.A. *Dynamics: Theory and Applications.* New York. McGraw-Hill, 1985.
13. McLeish, R.D. and Charnley, J. Abduction forces in the one-legged stance. *J. Biomech.* **3**: 191-209, 1970.
14. McMinn, R.M.H. and Hutchings, R.T. *Color Atlas of Human Anatomy.* Chicago. Year Book Medical Publ., Inc, 1985.
15. Nelder, J.A. and Mead, R. A simplex method for function minimization. *Comp. J.,* **7**: 308-313, 1964.

16. NEMETH, G. AND OHLSEN, H. Moment arm lengths of trunk muscles to the lumbrosacral joint obtained *in vivo* with computed tomography. *Spine*, **11**: 158-160, 1986.
17. NIEMI, J., NIEMINEN, H., TAKALA, E.-P. AND VIIKARI-JUNTURA, E. A static shoulder model based on a time-dependent criterion for load sharing between synergistic muscles. *J. Biomech.*, **29**: 451-460, 1996.
18. PIERRYNOWSKI, M.R. Analytic representation of muscle line of action and geometry. Pp. 215-256. In: ALLARD, P., STOKES, I.A.F. AND BLANCHI, J.P. (Eds.) *Three-dimensional Analysis of Human Movement*. Champaign, IL, Human Kinetics. 1995.
19. POPPEN, N.K. AND WALKER, P.S. Forces at the glenohumeral joint in abduction. *Clin. Orthop.* **135**: 165-170, 1978.
20. PRESS, W.H., TEUKOLSKY, S.A., VETTERLING, W.T. AND FLANNERY, B.P. *Numerical Recipes in C*. Second edition. New York. Cambridge Univ. Press. 1992.
21. RUGG, S.G., GREGOR, R.J., MANDELBAUM, B.R. AND CHIU L. *In vivo* moment arm calculations at the ankle using magnetic resonance imaging (RMN). *J. Biomech.*, **23**: 495-501, 1990.
22. SOECHTING, J.F., LACQUANITI, F. AND TERZUOLO, C.A. Coordination of arm movements in three-dimensional space. Sensorimotor mapping during drawing movement. *Neurosci.*, **17**: 295-311, 1986.
23. SPOOR, C.W. AND VAN LEEUWEN, J.L. Knee muscle moment arms from MRI and from tendon travel. *J. Biomech.*, **25**: 201-206, 1992.
24. VAN DER HELM, F.C.T. AND VEENBAAS, R. Modeling the mechanical effect of muscles with large attachment sites: application to the shoulder mechanism. *J. Biomech.*, **24**: 1151-1163, 1991.
25. VAN DER HELM, F.C.T., VEEGER, H.E.J., PRONK, G.M., VAN DER WOUDE L.H.V. AND ROZENDAL, R.H. Geometry parameters for musculoskeletal modeling of the shoulder system. *J. Biomech.*, **25**: 129-144, 1992.
26. VEEGER, H.E.J., VAN DER HELM, F.C.T., VAN DER WOUDE, L.H.V., PRONK, G.M. AND ROZENDAL R.H. Inertia and muscle constraction parameters for musculoskeletal modeling of the shoulder mechanism. *J. Biomech.*, **24**: 615-629, 1991.
27. WOOD, J.E., MEEK, S.G. AND JACOBSEN, S.C. Quantification of human shoulder anatomy for prosthetic arm control – II. Anatomy matrices. *J. Biomech.*, **22**: 309-325, 1989.
28. YAMAGUCHI, G.T., MORAN, D.W. AND SI, J. A computationally efficient method for solving the redundant problem in biomechanics. *J. Biomech.*, **28**: 999-1005, 1995.
29. ZAJAC, F.E. AND GORDON, M.F. Determining muscle's force and action in multi-articular movement. *Exerc. Sport. Sci. Rev.*, **17**: 187-230, 1989.
30. ZAJAC, F.E. AND WINTERS, J.M. Modeling musculoskeletal movement systems: Joint and body segmental dynamics, musculoskeletal actuation, and neuromuscular control. Pp. 121-148. In: WINTERS, J.M. AND WOO, S.L.-Y. (Eds.) *Multiple Muscle Systems: Biomechanics and Movement Organization*. Springer-Verlag, New York. 1990.