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Prediction of Antagonistic Muscle Forces Using Inverse Dynamic Optimization During Flexion/Extension of the Knee

This paper examined the feasibility of using different optimization criteria in inverse dynamic optimization to predict antagonistic muscle forces and joint reaction forces during isokinetic flexion/extension and isometric extension exercises of the knee. Both quadriceps and hamstrings muscle groups were included in this study. The knee joint motion included flexion/extension, varus/valgus, and internal/external rotations. Four linear, nonlinear, and physiological optimization criteria were utilized in the optimization procedure. All optimization criteria adopted in this paper were shown to be able to predict antagonistic muscle contraction during flexion and extension of the knee. The predicted muscle forces were compared in temporal patterns with EMG activities (averaged data measured from five subjects). Joint reaction forces were predicted to be similar using all optimization criteria. In comparison with previous studies, these results suggested that the kinematic information involved in the inverse dynamic optimization plays an important role in prediction of the recruitment of antagonistic muscles rather than the selection of a particular optimization criterion. Therefore, it might be concluded that a properly formulated inverse dynamic optimization procedure should describe the knee joint rotation in three orthogonal planes.

Introduction

Estimation of in-vivo muscle forces and joint reaction forces during various functional activities is of great importance in order to protect the knee joint from injury or to design rehabilitation exercise regimens for patients after joint reconstruction. Biomechanically, the knee joint is an indeterminate biomechanical system in nature, i.e., the number of unknown forces generated by each muscle, as well as joint contact forces and constraint moments, outnumber the equilibrium equations of the joint system. Hence, an inverse dynamic optimization analysis method (Crowninshield et al., 1978; Patriarco et al., 1981; Pedotti et al., 1978; Seireg and Arvikar, 1973, 1975) has been widely used to predict the muscle forces and joint reaction forces. This approach minimizes an optimization criterion under the constraints of equilibrium equations and upper limits of muscle stresses (Crowninshield et al., 1978; Dul et al., 1984; Kaufman, 1988), where an optimization criterion is usually derived according to the efficiency principle of neuromuscular control (Kaufman, 1988; Kaufman et al., 1991b).

While the inverse dynamic optimization method has been proven useful in predicting muscle forces from the measured kinematics of the segments, one major criticism is that this method does not properly predict co-contraction of antagonistic muscles (Collins, 1995; Hughes et al., 1995; Marras, 1988). For example, the inverse dynamic optimization was shown to be inappropriate to predict the antagonistic muscle activities during normal gait (Collins, 1995), where significant EMG activities of antagonistic muscles were measured. Much effort has been devoted to formulating a reasonable optimization criterion that could reflect the physiological activities developed within the muscles (Crowninshield and Brand, 1981; Granata and Marras, 1993; Happee, 1994; Kaufman et al., 1991b; Patriarco et al., 1981; Pedersen et al., 1987). As a result, numerous linear, nonlinear, and physiological optimization criteria have been proposed. However, a realistic prediction of antagonistic muscle activity is still a challenge in biomechanics.

Many previous studies simplified the knee using sagittal plane models (Arms et al., 1984; Challis and Kerwin, 1993; Collins, 1995; Crowninshield et al., 1978; Grood et al., 1984; Hirokawa et al., 1992; Jurist and Otis, 1985; Kaufman et al., 1991b, 1991c; Nisell et al., 1989; O'Connor, 1993; Patriarco et al., 1981; Pedotti et al., 1978; Seireg and Arvikar, 1975; Zavatsky and O'Connor, 1993). This treatment introduced rigid constraints to knee motion in coronal and transverse planes. External loads out of the sagittal plane will not affect the knee joint motion simulated using these models. In a recent study, Li et al. (1998, 1995) analyzed the muscle recruitment and its effect on joint reaction forces during knee joint exercise, using the optimization criterion proposed by Kaufman et al. (1991b). The knee joint isometric and isokinetic exercises were analyzed both in the sagittal plane and in the three orthogonal planes of the knee. Antagonistic muscle forces were predicted when the knee joint rotation was considered in three orthogonal planes. A similar phenomenon was also noticed by Glitsch and Baumann (1997) in their analysis of walking and running. These results demonstrated that the knee joint rotation in three orthogonal planes has to be involved in the inverse dynamic optimization procedure in order to predict more realistic muscle forces. Therefore, it was hypothesized in this paper that an optimization criterion (satisfying the efficiency criteria of neuromuscular control) would be able to predict antagonistic muscle forces during flexion/extension motion of the knee if the inverse dynamic optimization procedure was properly formulated by involving the knee joint rotation in three orthogonal planes. Four typical optimization criteria were selected to test the hypothesis.

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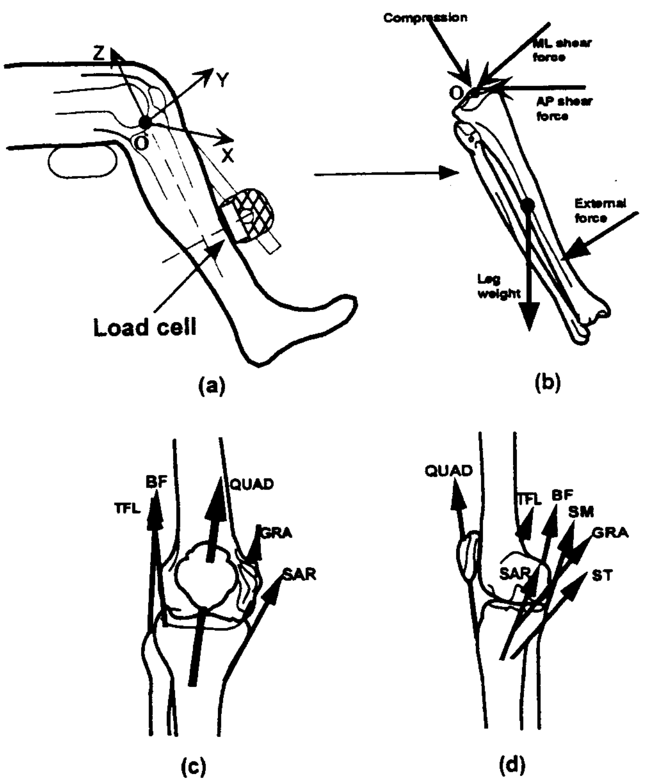

Fig. 1 Knee joint model used for inverse dynamic optimization analysis: (a) schematic diagram of flexion/extension motion of the knee; (b) free-body diagram of the tibia; (c) anterior view of the model; and (d) medial view of the model

Methods

Knee Joint Model. A computer model of a right human knee (Li et al., 1998, 1995) was utilized for dynamic analysis (Fig. 1). The model was constructed using CT and MRI images of a male subject with a body mass of 80 kg. The geometric shape of bony segments, the origin-to-insertion path of each muscle–tendon complex and the cross-sectional geometry of each muscle were specified. In this model, the tibia and fibula were assumed rigidly connected since relative motion between the two segments is small. Muscles crossing the knee joint were represented as vectors along the straight lines connecting their respective origin and insertion points. The quadriceps group (QUAD) included four extensor muscles: vastus lateralis, rectus femoris, vastus intermedius, and vastus medialis, and was represented by a vector oriented along the patellar tendon direction. The patellar tendon line of action and moment arm as functions of knee flexion angle were obtained from Smidt (1973) and van Eijden et al. (1985). In addition to the quadriceps, nine other muscles crossing the knee joint were modeled. These were: Tensor Fasciae Latae (TFL), Sartorius (SAR), Gracillis (GRA), Semimembranosus (SM), Semitendinosus (ST), Biceps Femoris Long Head (BFLH), Biceps Femoris Short Head (BFSH), Gastrocnemius Medial (GASM), and Gastrocnemius Lateral (GASL).

In the local coordinate system of the tibia, the longitudinal axis of the tibia was defined as the Z axis, The central point between the two tibial spines was chosen as the center of the knee joint and was used as the origin of the local coordinate system of the tibia. The tibia was allowed to rotate with respect to the knee center in three orthogonal planes (Fig. 1), i.e., flexion/extension in the sagittal plane (about the Y axis), varus/valgus rotation in the coronal plane (about the X axis), and internal/external rotation in the transverse plane (about the Z axis). Even though tibial translation has been reported in the literature, it was not included in this model. Thus, the joint was assumed to have three degrees of freedom in rotation.

As shown in the free-body diagram of Fig. 1(b), the external force system of the tibia was balanced by its internal force system. The external force system included applied forces, body weight, and the dynamic inertial forces and moments of the knee. The internal force system of the tibia consisted of muscle forces and joint reaction (or constraint) forces and moments. The joint reaction forces and moments consisted of the resultants of joint contact forces and ligamentous forces. Therefore, a set of six force and moment equilibrium equations can be obtained from the free-body analysis of the tibia and written as (Kaufman et al., 1991a)

$$\sum_{i=1}^{10} F_i^M \vec{\tau}_i + \mathbf{F}^j = \mathbf{F}^e,$$

$$\sum_{i=1}^{10} F_i^M(\mathbf{r}_i \times \vec{\tau}_i) + \mathbf{T}^j = \mathbf{T}^e, \qquad (1)$$

where F_i^M represents the magnitude of the force vector of the ith muscle, $\vec{\tau}_i$ represents a force unit vector of the ith muscle, $\mathbf{F}^j$ and $\mathbf{T}^j$ represent the vectors of joint constraint forces and moments, $\mathbf{F}^e$ and $\mathbf{T}^e$ represent the vectors of external (or intersegmental) forces and moments due to the external force system of the tibia, and $\mathbf{r}_i$ represents the location of the insertion of the ith muscle on the tibia with respect to the joint center. The muscle force unit vector, $\vec{\tau}_i$, was calculated along the action line of the muscle at each flexion angle, which connects the insertion and origin points of the muscle (Crowninshield and Brand, 1981; Dostal and Andrews, 1981; Jensen and Davy, 1975; Jensen and Metcalf, 1975; Patriarco et al., 1981).

The intersegmental force and moment vectors ($\mathbf{F}^e$ and $\mathbf{T}^e$) can be calculated using an inverse dynamic procedure (i.e., using joint kinematics, external loads, and inertial properties) (Kaufman et al., 1991b, c). Each muscle force magnitude represented an unknown variable. Since the knee was assumed to rotate frictionlessly about the knee center, the muscles were assumed to provide forces to keep the joint stable in rotation. Thus, $\mathbf{T}^j$ will be eliminated from the equilibrium equations. These equilibrium equations (three force and three moment equilibrium equations) contain thirteen unknowns: ten muscle force magnitudes and three components of joint reaction forces. The contribution of ligaments is assumed to be included in the joint reaction forces. This represents a statically indeterminate problem.

In order to solve muscle forces and joint reaction forces, an optimization method has been adopted where an objective function, "J," is minimized under the constraints of the equilibrium equations, nonnegative muscle forces (i.e., the muscles can only generate tensile forces) and upper bounds of muscle stresses (Crowninshield and Brand, 1981; Crowninshield et al., 1978; Pedotti et al., 1978). The nonnegative muscle force constraint means $F_i^M \geq 0$. Therefore, the calculation of muscle forces and joint reaction forces can be written in the following constraint optimization procedure:

$$\text{Minimize } J$$

$$(a) \quad \sum_{i=1}^{10} F_i^M \vec{\tau}_i + \mathbf{F}^j = \mathbf{F}^e,$$

$$(b) \quad \sum_{i=1}^{10} F_i^M(\mathbf{r}_i \times \vec{\tau}_i) = \mathbf{T}^e,$$

$$(c) \quad 0 \leq F_i^M/A_i \leq \sigma_i, \quad i = 1, 10, \qquad (2)$$

where σ_i is the maximum stress and A_i is the physiological cross-sectional area of the ith muscle (Brand et al., 1982). The third constraint equation (Eq. 2(c)) represents the nonnegative muscle force constraint where the stress in every muscle cannot exceed a maximum value (An et al., 1984; Crowninshield et al., 1978; Pedotti et al., 1978). The optimization procedure of Eq. (2) can then be used to calculate individual muscle forces and joint reaction forces using three-dimensional kinematic and kinetic data of the joint.

Optimization Criteria for Inverse Dynamic Optimization Four typical optimization criteria were examined in this paper:

1 Minimization of total muscle force:

$$\text{Minimize } J_1 = \sum_{i=1}^{10} F_i^M. \tag{3}$$

This criterion assumed that the summation of the magnitude of individual muscle forces should be minimized for dynamic equilibrium of the knee joint (MacConnaill, 1967).

2 Minimization of the joint moment:

$$\text{Minimize } J_2 = \sum_{i=1}^{10} F_i^M |\mathbf{r}_i \times \hat{\tau}_i|. \tag{4}$$

This criterion minimizes the total moment generated by all muscles (Seireg and Arvikar, 1975) with respect to the center of the knee joint.

3 Minimization of total cubic muscle stress:

$$\text{Minimize } J_3 = \sum_{i=1}^{10} (F_i^M/A_i)^3. \tag{5}$$

This nonlinear optimization criterion was proposed by Crowninshield and Brand (1981).

4 Minimization of muscular activation: In this model, the muscle was modeled as a contractile element in parallel with a passive element connected to a series elastic element (tendon) that was taken to be very stiff relative to the parallel elastic element. The muscle force was adjusted for its activation length and relative velocity of insertion points. The force was oriented along the straight line connecting the muscle's origin and insertion. This force can be expressed as (Kaufman et al., 1991a)

$$\mathbf{F}^M = \alpha \cdot \mathbf{F}_l \cdot \mathbf{F}_v + \mathbf{F}_{pe}, \tag{6}$$

where α is the neuromuscular activation, $\mathbf{F}_l$ represents the force–tension relationship, $\mathbf{F}_v$ represents the force–velocity relationship, and $\mathbf{F}_{pe}$ is the force due to passive elements of the muscle. An optimization method which used the muscular activation α as a physiological optimization criterion (Kaufman et al., 1991a) was adopted in this paper for distributing muscle and joint reaction forces, i.e.,

$$\text{Minimize } J_4 = \alpha. \tag{7}$$

This function has been referred to as physiological optimization criterion in later discussion.

Knee Flexion/Extension Exercise

Isokinetic Flexion/Extension. The knee model described previously was used to analyze the joint motion measured from an isokinetic knee exercise by Kaufman et al. (1991c) on five normal male subjects at angular speed of 60 deg/s with maximal voluntary effort in both flexion and extension. Angular displacement of the knee was measured with a triaxial electrogoniometer (Chao, 1980). The external force applied to the tibia was measured with a three-component load cell (Fig. 1). Angular velocities and accelerations were calculated by time differentiation of the angular displacement (Woltring, 1986). The inverse dynamic problem was formed by proceeding from the known displacement history and incorporating the external loading and tibia inertial properties to yield the external intersegmental forces and moments (Kaufman et al., 1995, 1991b, 1991c). Averaged data for five subjects were obtained from Kaufman et al. (1995). These forces and moments describe the dynamic character of the right tibia during the isokinetic flexion/extension exercise at a speed of 60 deg/s.

Isometric Extension. Isometric knee extension was simulated by fixing the knee at a selected flexion angle. To keep the joint at a fixed flexion angle, external forces and moments applied on the knee joint were balanced by muscle forces. The inverse dynamic optimization procedure described above was utilized to calculate the muscle forces and joint reaction forces when the subject performed isometric knee extension at 0, 20, 40, 60, 80, and 100 deg of flexion. At each selected flexion angle, a flexion moment of 48.0 Nm combined with either an internal moment or external moment of 2.4 Nm was applied to the knee (Li et al., 1998, 1995).

Results

Isokinetic Knee Exercise. Muscle forces predicted to be nearly identical by using different optimization criteria in the inverse dynamic optimization procedure are shown in Fig. 2. The minimization of cubed muscle stress (J_3) and the minimization of joint moments (J_2) predicted almost identical results. All optimization criteria were able to predict simultaneous flexor muscle forces over the whole range of flexion motion of the exercise (0–100 deg), except that only slight activity was predicted for the GASL muscle. The quadriceps, as antagonistic muscles during knee flexion, showed relatively small co-contraction at full extension as well as beyond 50 deg of flexion. The optimization procedure of minimizing muscular activation (J_4) predicted stronger antagonistic activation of the quadriceps than other linear and nonlinear optimization criteria.

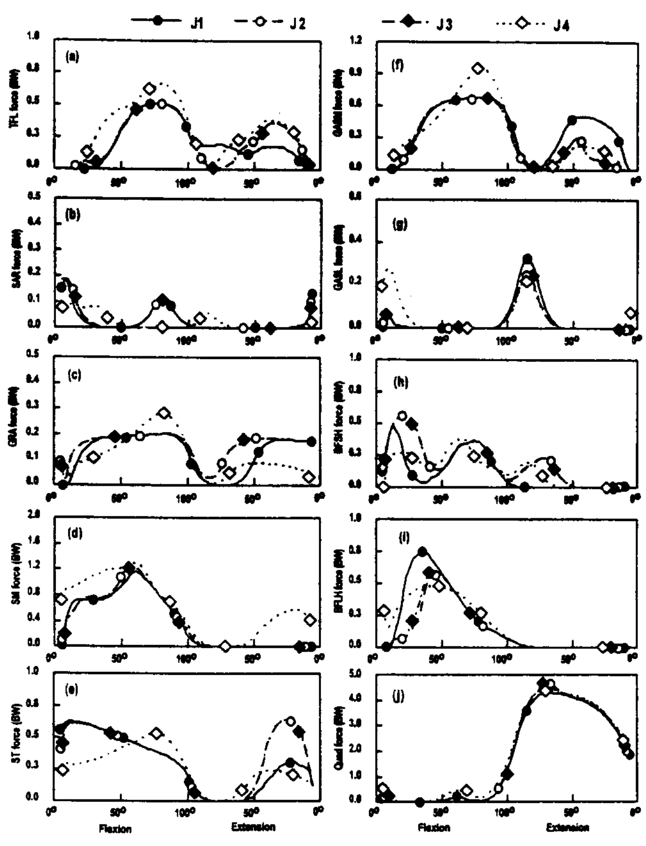

Fig. 2 Muscle forces predicted using different optimization criteria during isokinetic exercise at 60 deg/s. All forces have been normalized with respect to the body weight. (*a*) TFL—Tensor Fasciae Latae; (*b*) SAR—Sartorius; (*c*) GRA—Gracilis; (*d*) SM—Semimembranosus; (*e*) ST—Semitendinosus; (*f*) BFLH—Biceps Femoris Long Head; (*g*) BFSH—Biceps Femoris Short Head; (*h*) GASM—Gastrocnemius Medial; (*i*) GASL—Gastrocnemius Lateral; (*j*) QUAD—Quadriceps group.

When the knee was extended from 100 deg to full extension, all optimization criteria predicted strong antagonistic contractions of most flexor muscles except the SM and BFLH muscles. The SM muscle was predicted to be active only by minimizing muscular activation, while the BFLH muscle was shown to be inactive by all of the optimization criteria. The forces of QUAD muscles were predicted similarly using all of the optimization criteria. The optimization criterion of minimizing cubed muscle stress predicted a slightly higher maximal force of the QUAD muscles than other optimization criteria. Maximal forces of the QUAD muscles occurred when the knee was extended between 65–75 deg of flexion.

Joint reaction forces during the isokinetic exercise calculated using the four different optimization criteria are shown in Fig. 3. Anterior–posterior shear forces are related to posterior and anterior tibial translation and are mainly resisted by the posterior and anterior cruciate ligaments, respectively. The anterior shear forces (resisting posterior tibial translation) are shown positive and posterior shear forces (resisting anterior tibial translation) negative in the figure. The maximal anterior shear force was predicted to be 2.3 BW by the three linear and nonlinear optimization criteria at 60 deg of knee flexion during flexion portion of the exercise and 2.6 BW by minimizing muscular activation (Fig. 3(*a*)). The linear optimization criteria (J_1 and J_2) predicted 0.34 BW posterior tibial shear force when the knee extends to full extension, the nonlinear optimization criterion (J_3) predicted 0.312 BW, and the physiological optimization criterion (J_4) predicted 0.308 BW.

All optimization criteria predicted similar joint compressive forces as shown in Fig. 3(*b*), with slightly higher compression predicted by minimizing muscle activation. A force of over two times body weight in compression was predicted during the flexion portion (between 10–70 deg of flexion) of the exercise. The maximal compression of 5.2 BW was predicted by the optimization criterion of minimizing muscle activation at a flexion angle of 46 deg during the extension portion of the exercise.

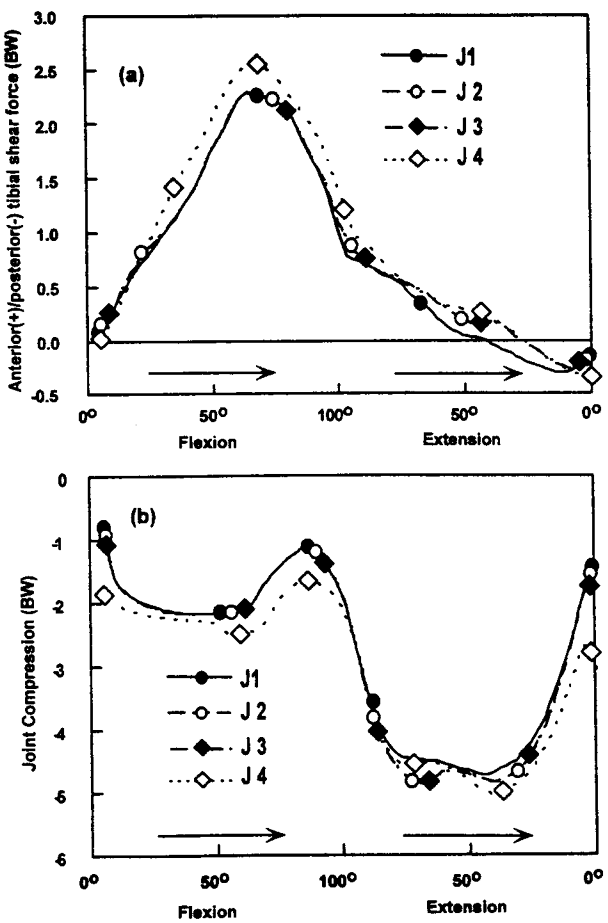

Fig. 3 Tibiofemoral joint reaction forces during isokinetic exercise at 60 deg/s. Forces have been normalized with respect to the body weight. (*a*) Anterior–posterior shear forces; (*b*) joint compressive forces.

Isometric Extension Exercise. The muscle forces of the knee predicted by using the four optimization criteria are shown in Fig. 4, where all the flexor muscles were integrated into the hamstrings group (Ham). When the knee extended to resist a flexion moment of 48 Nm and an internal moment of 2.4 Nm, the quadriceps force was predicted to be approximately 1.5 BW from full extension to 80 deg of flexion by all optimization criteria and 1.9 BW at 100 deg of flexion (Fig. 4(*a*)). Antagonistic contraction of hamstrings was predicted to be below 0.5 BW over the whole range of flexion and decreased as flexion angle increased (Fig. 4(*b*)).

While under the application of the flexion moment and an external moment of 2.4 Nm, the quadriceps forces were predicted to be high at both low and high flexion angles with a magnitude of approximately 2.0 BW at full extension (Fig. 4(*c*)). The antagonistic contraction of the hamstrings was predicted to be over 1.0 BW at full extension and decreased as the flexion angle increased (Fig. 4(*d*)). The optimization criterion of minimizing muscular activation predicted a higher hamstring force than other optimization criteria when the knee was at full extension.

Maximum posterior tibial shear forces were predicted to occur at full extension under the combined flexion and internal moment, which was approximately 0.4 BW (Fig. 5(*a*)). As the flexion angle increased higher than 20 deg, the knee joint carried an anterior tibial shear load. Axial joint compression during the isometric extension of the knee was predicted to be approximately 2.0 BW over the whole range of flexion angles by all optimization criteria under the combined moment (Fig. 5(*b*)).

While under the combined flexion and external moment, the posterior tibial shear force was predicted to be 0.6 BW at full extension (Fig. 5(*c*)). The joint was under posterior tibial shear force until 40 deg of flexion. Axial compression was predicted to be 3.0 BW at full extension and decreased as the flexion angle increased (Fig. 5(d)). Beyond 20 deg of flexion, the axial compression was predicted to be almost constant with a value of 2.0 BW. The optimization criterion of minimizing muscular activation predicted slightly higher axial compression than other linear and nonlinear criteria.

Discussion

Muscle contraction and joint reaction forces of the knee during an isokinetic knee exercise and a simulated isometric knee extension exercise were predicted using an analysis procedure of inverse dynamic optimization. The inverse dynamic analysis included the knee joint motion of flexion/extension, varus/valgus, and internal/external rotations. In general, similar patterns of muscle contraction forces were predicted by using all four optimization criteria. Axial compression and anterior tibial shear forces of the joint were also predicted similarly by these optimization criteria. These results verified our hypotheses that the optimization criteria, which satisfy the efficiency principles of neuromuscular control, were able to predict antagonistic muscle activities. If joint reaction forces are of major interest in the problem, a linear optimization criterion will be able to predict results similar to those predicted by complex nonlinear or physiological optimization procedures as shown in Figs. 3 and 5.

Similar to other studies of calculation of muscle contraction forces, validation of the results presents a challenge. EMG patterns have been utilized to validate the muscle force calculation temporally (Collins, 1994, 1995; Crowninshield and Brand, 1981; Kaufman et al., 1991b; Li et al., 1998; Patriarco et al.,

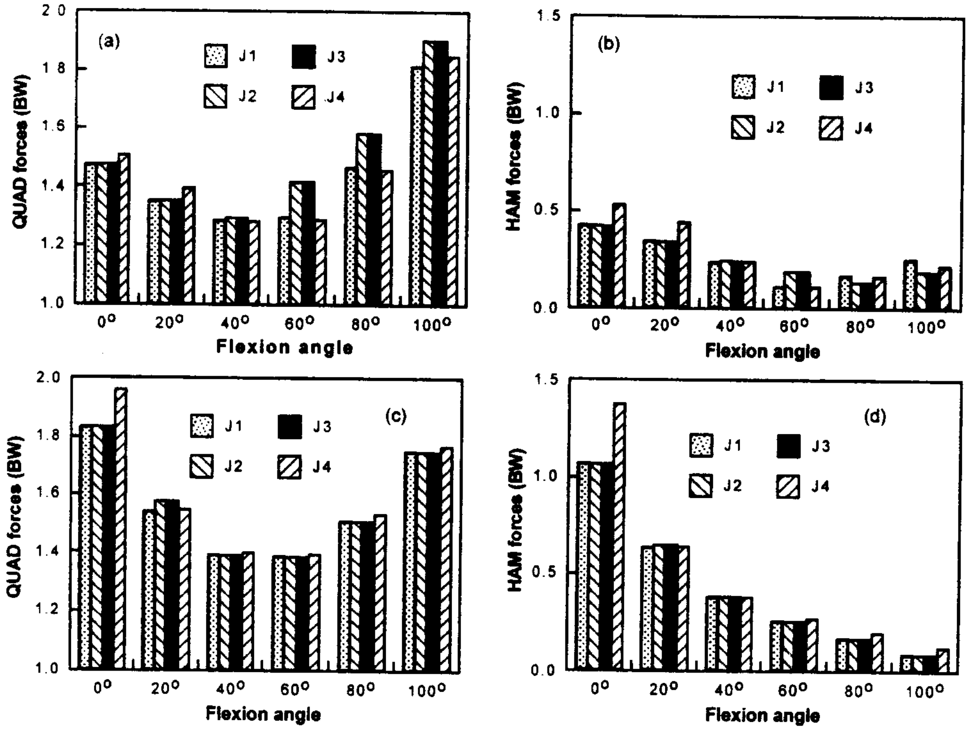

Fig. 4 (*a*) Quadriceps and (*b*) hamstring muscle forces during isometric knee extension exercise with an applied internal moment, and (*c*) quadriceps and (*d*) hamstring muscle forces with an applied external moment

1981; Pedersen et al., 1987). A qualitative comparison of the integrated EMG data (averaged from the measurement on the five subjects) of Kaufman et al. (1991b) to the muscle forces calculated using different optimization criteria is shown in Fig. 6 for GRA, SM, ST, BFSH, GASM, and QUAD muscles. In general, all optimization criteria predicted muscle forces when EMG activity was present. The muscle forces predicted by minimizing muscular activation showed a better match in patterns with the EMG history than other linear and nonlinear optimization criteria, as shown in Fig. 6.

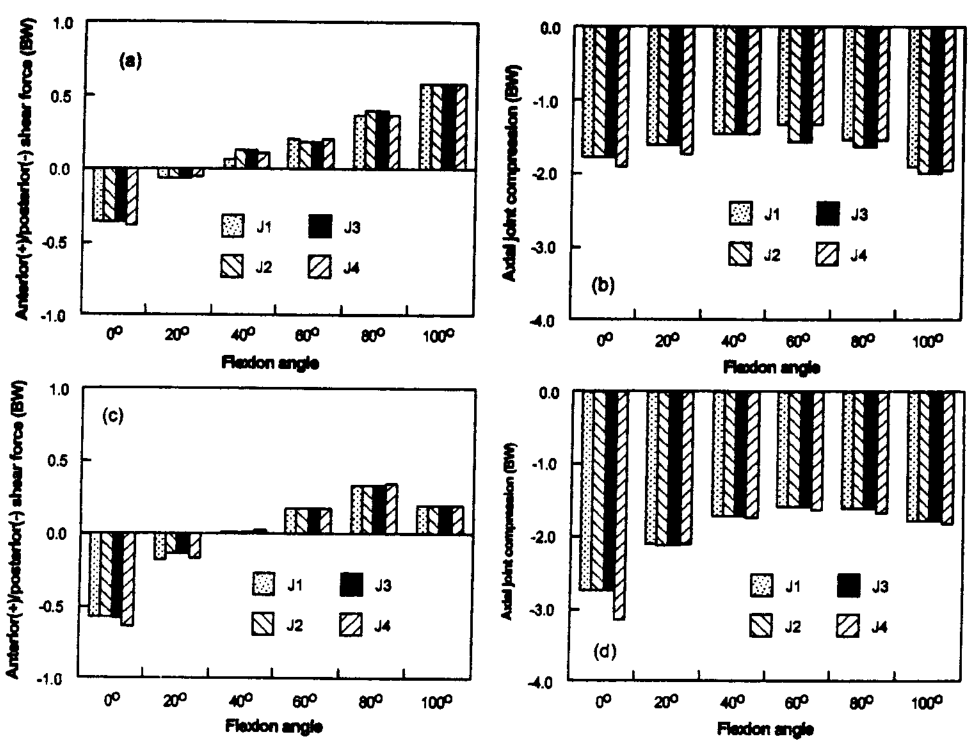

Fig. 5 (*a*) Anterior-posterior tibial shear forces and (*b*) joint compressive forces during isometric knee extension exercise with an applied internal moment, and (*c*) anterior-posterior tibial shear forces and (*d*) joint compressive forces with an applied external moment

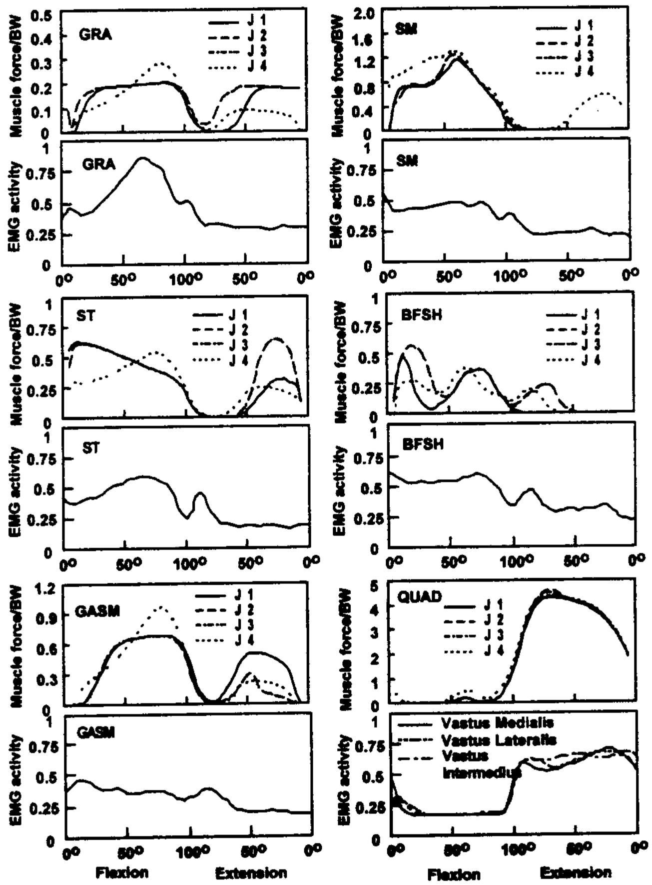

Fig. 6 Comparison of muscle forces predicted using different optimization criteria with measured EMG data during an isokinetic motion cycle at a speed of 60 deg/s

Comparison of different optimization criteria used in inverse dynamic optimization analysis has been previously pursued in order to evaluate their capability to predict synergistic and antagonistic muscle activities (Challis and Kerwin, 1993; Collins, 1995; Crowninshield and Brand, 1981; Kaufman et al., 1991b; Patriarco et al., 1981; Pedersen et al., 1987; etc.). Nonlinear optimization methods were shown to be superior over linear optimization procedures (Collins, 1995; Crowninshield and Brand, 1981; Kaufman et al., 1991b), while optimization using physiological optimization criteria was shown to predict muscle activities more reasonably than both linear and nonlinear optimization methods (Collins, 1995; Kaufman et al., 1991b; Patriarco et al., 1981). However, in most of these studies, the joint motion was analyzed in the sagittal plane of the knee, which restrained the knee rotation in other planes.

A muscle model is three dimensional in nature (Brand et al., 1982). Muscles have both primary and secondary functions (Pedersen et al., 1987). If extensor muscles contract to cause knee extension by their primary function, the secondary function will simultaneously cause knee joint motion in other degrees of freedom in addition to the primary extension motion. This indicates that one of the intrinsic biomechanical characteristics of the knee joint is its three-dimensional motion under muscle action. The three-dimensional stability of the knee requires synergistic action of the muscle and ligamentous forces, and joint contact pressure. Andriacchi et al. (1984) suggested that the antagonistic muscle activities provide medial–lateral stability to the knee. Draganich et al. (1989) noted that antagonistic muscle activities act synergistically with the anterior cruciate ligament to prevent anterior displacement of the tibia, while Baratta et al. (1988) speculated that antagonistic muscle function equalizes the joint articular surface pressure distribution. Therefore, modeling the knee joint motion only in the sagittal plane introduces rigid artificial constraints on coronal and transverse plane rotations.

According to this discussion, antagonistic muscle forces are therefore necessary to balance the secondary function of the muscles (Li et al., 1998, 1995). It may be concluded that in order to simulate muscle contraction forces appropriately, an inverse dynamic optimization procedure has to be formulated properly to include knee joint motion in three dimensions. All optimization criteria adopted in this paper were able to predict similar antagonistic muscle activities, axial joint compression, and anterior–posterior tibial shear forces.

The knee model used in this study considered muscles as the sole contributors to balance the intersegmental moments. The moments generated from ligament tension as well as joint contact were integrated into the muscle contributions. This treatment may overestimate the function of muscles in keeping the dynamic stability of the knee. Thus, the predicted muscle forces and joint reaction forces may represent an upper bound for the corresponding tissue responses. Tibial translation was not simulated in this model. Consideration of its effect on prediction of muscle forces and joint reaction forces depends on an accurate measurement of tibial translation. Further development of a dynamic knee joint model should examine the effect of tibial translation on the intersegmental forces and moments as well as the prediction of muscle forces and joint reaction forces.

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