Computer Simulation of Surgical Treatment for Equinus Deformity in Cerebral Palsy

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Introduction

Equinus is the most common deformity in patients with cerebral palsy. The cause of the deformity is a combination of increased spasticity of the triceps surae muscles combined with weakness of the ankle dorsiflexors. Inadequate opposition from the tibialis anterior muscle results in a muscle imbalance of the triceps surae, which leads to static contracture over time in a growing child (Gage & Öunpuu, 1991). Treatment options for equinus deformity includes repeated passive stretching, bracing, Botulinum toxin injection, or surgical treatment. Surgery to the heel cord is a common type of therapy, which has been used for over a century. This type of surgery was first introduced by Little (1862).

Many different surgical procedures have been described for lengthening of the triceps surae. Currently, two basic types of surgical procedures are used for treating equinus deformity. The two principle surgical approaches involve either (a) Z-plasty or sliding lengthening forms of tendo Achilles lengthening (Hoke, 1921; White, 1943), or (b) fascial lengthening of the aponeurosis covering the gastrocnemius. Fascial lengthening of the gastrocnemius was first described by Vulpian and Stoffel (1920), and later modifications were described by Strayer (1950) and Baker (1954). Both procedures carry a risk of overcorrection, reduced strength (Gaines & Ford, 1984; Grabe & Thompson, 1979), and the development of crouch gait (Sutherland & Cooper, 1978). The purpose of this study was to compare the strength preservation characteristics of these two types of surgical procedures using a computer model.

Methods

The model used in this study is an anatomical model that represents the muscle orientation, size, and architectural characteristics.

The muscle orientation was calculated using a straight-line model. This approach
is reasonable on the basis of a study that compared skeletal muscle length when using centroid lines to a straight-line analysis (Jensen & Davy, 1975). Origin and insertion coordinate data for the plantarflexors were used to calculate the muscle line of action (White et al., 1989). The ankle plantarflexors included the soleus, medial and lateral gastrocnemius, tibialis posterior, flexor digitorum longus, flexor hallucis longus, and peroneus longus and peroneus brevis. Each muscle was given a three-dimensional coordinate expressed in one of three Cartesian reference frames fixed to the femur, tibia, or foot. The muscle origin insertions and the position of the knee joint center were transformed to a coordinate system attached to the tibia with an origin at the ankle joint center. To quantify the force and moment effects of the muscles, the location of the origin

$$\mathbf{r}_o = x_o \mathbf{i} + y_o \mathbf{j} + z_o \mathbf{k}$$

and the location of the insertion

$$\mathbf{r}_i = x_i \mathbf{i} + y_i \mathbf{j} + z_i \mathbf{k}$$

of the muscle relative to the localized coordinate system fixed at the ankle joint center was specified, where \( \mathbf{i}, \mathbf{j}, \) and \( \mathbf{k} \) are unit vectors that correspond to the positive \( x, y, \) and \( z \) axes of the tibia, respectively. The muscle force, \( \mathbf{F}_i \), was expressed as

$$\mathbf{F}_i = |\mathbf{F}_i| \mathbf{\tau}_i$$

where \( |\mathbf{F}_i| \) is the magnitude of the muscle force. Thus, using the straight line muscle model,

$$\mathbf{\tau}_i = \frac{\mathbf{r}_o - \mathbf{r}_i}{|\mathbf{r}_o - \mathbf{r}_i|}$$

where \( \mathbf{\tau}_i \) is a unit muscle force vector for the \( i \)th muscle. The moment arm was defined as the force times the perpendicular distance from the line of action for the force to the axis of rotation. The axis of rotation was assumed to be the joint center. The muscle moment could be expressed as a moment generated by unit muscle force. Mathematically, this is expressed as

$$\mathbf{m}_i = \mathbf{r}_i \times \mathbf{\tau}_i$$

where \( \mathbf{m}_i \) is the moment associated with the \( i \)th muscle and \( \mathbf{r}_i \) is a position vector from the joint center of rotation to the muscle insertion.

The necessary features used to describe the morphology of the muscle were its physiological cross-sectional area (PCSA), muscle architecture, and muscle stress limit. The moment arm of the muscle merely indicates the efficacy of the muscle for rotation of a body segment about that particular joint axis. The force that can be actively generated by each muscle is proportional to the PCSA (An et al., 1981; Brand et al., 1981). The rationale is simply that the cross-sectional area of a muscle is proportional to the number of its fibers, and the individual muscle fiber is the basic element that generates the active tension. The PCSA data used in this model was taken from Wickiewicz et al. (1983) and Huijing (1985). Muscle fiber architectural characteristics were also included in the model. The index of architecture (Woittiez et al., 1984) was used to define differing architectural characteristics of the muscles. The index of architecture was defined as