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Short communication

Error propagation from kinematic data to modeled muscle-tendon lengths during walking

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ABSTRACT

Kinematic data from 3D gait analysis together with musculoskeletal modeling techniques allow the derivation of muscle-tendon lengths during walking. However, kinematic data are subject to soft tissue artifacts (STA), referring to skin marker displacements during movement. STA are known to significantly affect the computation of joint kinematics, and would therefore also have an effect on muscle-tendon lengths which are derived from the segmental positions. The present study aimed to introduce an analytical approach to calculate the error propagation from STA to modeled muscle-tendon lengths. Skin marker coordinates were assigned uncorrelated, isotropic error functions with given standard deviations accounting for STA. Two different musculoskeletal models were specified; one with the joints moving freely in all directions, and one with the joints constrained to rotation but no translation. Using reference kinematic data from two healthy boys (mean age 9 y 5 m), the propagation of STA to muscle-tendon lengths was quantified for semimembranosus, gastrocnemius and soleus. The resulting average SD ranged from 6% to 50% of the normalized muscle-tendon lengths during gait depending on the muscle, the STA magnitudes and the musculoskeletal model. These results highlight the potential impact STA has on the biomechanical analysis of modeled muscle-tendon lengths during walking, and suggest the need for caution in the clinical interpretation of muscle-tendon lengths derived from joint kinematics.

1. Introduction

Musculoskeletal models are an important aspect of the biomechanical analysis of human locomotion, providing insight into changes in muscle-tendon lengths during both normal and pathological gait (Arnold et al., 2005, 2006; Delp et al., 1996; Schutte et al., 1997; Wren et al., 2004). Kinematic data from 3D gait analysis are commonly used to derive skeletal motion and consequently muscle-tendon lengths. However, kinematic data are affected by soft tissue artifacts (STA) which originate from movements of skin markers with respect to the underlying bones. STA are a major error source in the determination of rigid bone movement (Leardini et al., 2005); and significantly affect the computation of joint kinematics, particularly in the frontal and transversal plane (Cappozzo et al., 1996; Chèze, 2000; Ramakrishnan and Kadaba, 1991; Stagni et al., 2005; Woltring et al., 1985). Studies quantifying STA through use of intracortical pins (Benoit et al., 2006; Fuller et al., 1997; Reinschmidt et al., 1997), external fixators (Cappozzo et al., 1996) or fluoroscopy-based tracking (Stagni et al., 2005) have reported STA ranging from a few millimeters for shank markers through to 40 mm for femoral epicondyle markers in the anterior–posterior direction during 120° knee flexion.

Although the effect of STA on joint angles has been described, the error propagation from STA to muscle-tendon lengths has not been previously analyzed. The objective of the present study was to introduce an analytical method for calculating the error propagation from STA to modeled muscle-tendon lengths. The theoretical framework was applied to reference kinematic data of two subjects, and the errors in muscle-tendon lengths of semimembranosus (SM), gastrocnemius (GA) and soleus (SL) were quantified. These three lower limb muscles were chosen as they are often shortened in children with cerebral palsy, and have been modeled in previous studies (Arnold et al., 2006; Delp et al., 1996; Schutte et al., 1997; Wren et al., 2004).

2. Subjects and methods

2.1. Reference kinematic data and musculoskeletal model

Ethical approval was given by the NZ Northern Y Regional Ethics Committee. Kinematic data of two healthy boys (mean age

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9 y 5 m) walking at self-selected speed were acquired on an 8-camera VICON Workstation Version 5.0 (Oxford Metrics Ltd., Oxford, England) at 100 Hz. One representative trial of each subject served as reference data.

Anatomical coordinate systems were defined according to ISB recommendations (Wu, 2002), enabling the description of segmental kinematics. Initially, the segments were allowed to move freely in all directions. However, joint constraints have been shown to improve the estimation of skeletal motion (Lu and O'Connor, 1999), and were as such expected to reduce the errors in muscle-tendon lengths. To corroborate this hypothesis, a second model was specified with the hip, knee and ankle joints constrained to three degrees of freedom; that is rotation but no translation.

The muscle attachment points were predefined as local coordinates $\mathbf{m}_i^l$ with respect to the anatomical coordinate systems. The corresponding global coordinates $\mathbf{m}_i^g$ during walking were derived via a coordinate transformation between the anatomical $[\mathbf{f}_1\ \mathbf{f}_2\ \mathbf{f}_3]$ and the laboratory coordinate system $[\mathbf{e}_1\ \mathbf{e}_2\ \mathbf{e}_3]$. The coordinate transformation was described by means of a rotation matrix $\mathbf{R}$ and a translation vector $\mathbf{t}$ that is

$$\mathbf{m}_i^g = [\mathbf{R}]\mathbf{m}_i^l + \mathbf{t}, \tag{1}$$

whereby the rotation matrix $\mathbf{R}$ was computed from the dot product between the two bases as

$$\mathbf{R}_{ij} = \mathbf{e}_i \cdot \mathbf{f}_j. \tag{2}$$

Muscle-tendon length was defined as absolute length between attachment points and was normalized with respect to the mean length during gait.

2.2. Error propagation analysis

The error propagation was analytically described assuming normally distributed errors in the reference skin marker location. Two distinct standard deviations (SD) were assigned to the error function of each coordinate relating to different STA magnitudes: (a) SD 4 mm for skin markers on thigh and SD 3 mm for all other markers; (b) SD 9 mm for thigh and SD 6 mm for all other skin markers, respectively.

The error propagation analysis was divided into several steps to allow for an analytically tractable formulation. For each step, a differentiable function was defined $f(\mathbf{x}_1, \mathbf{x}_2, \ldots, \mathbf{x}_N)$. Assuming independent and normally distributed input variables $\mathbf{x}_1, \mathbf{x}_2, \ldots, \mathbf{x}_N$ with given SD of $\Delta\mathbf{x}_1, \Delta\mathbf{x}_2, \ldots, \Delta\mathbf{x}_N$ around the reference values, the error Δf in the dependent variable was derived from the Addition in Quadrature that is

$$\Delta f = \sqrt{\sum_{i=1}^{N}\left(\frac{\partial f}{\partial x_i}\Delta x_i\right)^2}, \tag{3}$$

whereby the partial derivatives were evaluated at the reference values (Taylor, 1982).

According to Eq. (3), the errors $\Delta\mathbf{f}_i$ of the unit vectors $\mathbf{f}_i$ derived from the position data of skin markers $\mathbf{p}_i$ as

$$\begin{aligned}\mathbf{f}_1 &= \frac{1}{|\mathbf{p}_1 - \mathbf{p}_2|}(\mathbf{p}_1 - \mathbf{p}_2),\\ \mathbf{f}_2 &= \frac{1}{|\mathbf{p}_3 - \mathbf{p}_2|}(\mathbf{p}_3 - \mathbf{p}_2),\\ \mathbf{f}_3 &= \mathbf{f}_1 \times \mathbf{f}_2\end{aligned} \tag{4}$$

were computed from

$$\begin{aligned}\Delta\mathbf{f}_1 &= \sqrt{\left(\frac{\partial\mathbf{f}_1}{\partial\mathbf{p}_1}\Delta\mathbf{p}_1\right)^2 + \left(\frac{\partial\mathbf{f}_1}{\partial\mathbf{p}_2}\Delta\mathbf{p}_2\right)^2},\\ \Delta\mathbf{f}_2 &= \sqrt{\left(\frac{\partial\mathbf{f}_2}{\partial\mathbf{p}_3}\Delta\mathbf{p}_3\right)^2 + \left(\frac{\partial\mathbf{f}_2}{\partial\mathbf{p}_2}\Delta\mathbf{p}_2\right)^2},\\ \Delta\mathbf{f}_3 &= \sqrt{\left(\frac{\partial\mathbf{f}_3}{\partial\mathbf{f}_1}\Delta\mathbf{f}_1\right)^2 + \left(\frac{\partial\mathbf{f}_3}{\partial\mathbf{f}_2}\Delta\mathbf{f}_2\right)^2},\end{aligned} \tag{5}$$

whereby $\Delta\mathbf{p}_i$ accounts for STA.

Given Eq. (5), the errors $\Delta\mathbf{R}$ and $\Delta\mathbf{t}$ that propagated from the anatomical coordinate system $\mathbf{F} : [\mathbf{f}_1\ \ \mathbf{f}_2\ \ \mathbf{f}_3]$ to the rotation matrix $\mathbf{R}$ and translation vector $\mathbf{t}$ (Eq. (1)) were derived as

$$\begin{aligned}\Delta\mathbf{R} &= \sqrt{\left(\frac{\partial\mathbf{R}}{\partial\mathbf{F}}\Delta\mathbf{F}\right)^2},\\ \Delta\mathbf{t} &= \sqrt{\left(\frac{\partial\mathbf{t}}{\partial\mathbf{R}}\Delta\mathbf{R}\right)^2 + \left(\frac{\partial\mathbf{t}}{\partial\mathbf{p}_2}\Delta\mathbf{p}_2\right)^2},\end{aligned} \tag{6}$$

whereby $\mathbf{p}_2$ denotes the origin of the anatomical coordinate system $\mathbf{F}$.

Given Eq. (6), the error $\Delta\mathbf{m}_i^g$ that propagated to the global coordinates of the muscle attachment point $\mathbf{m}_i^g$ was computed from

$$\Delta\mathbf{m}_i^g = \sqrt{\left(\frac{\partial\mathbf{m}_i^g}{\partial\mathbf{R}}\Delta\mathbf{R}\right)^2 + \left(\frac{\partial\mathbf{m}_i^g}{\partial\mathbf{t}}\Delta\mathbf{t}\right)^2}, \tag{7}$$

which resulted in the error Δl of muscle-tendon length

$$l = |\mathbf{m}_1^g - \mathbf{m}_2^g| \tag{8}$$

as

$$\Delta l = \sqrt{\left(\frac{\partial l}{\partial\mathbf{m}_1^g}\Delta\mathbf{m}_1^g\right)^2 + \left(\frac{\partial l}{\partial\mathbf{m}_2^g}\Delta\mathbf{m}_2^g\right)^2}. \tag{9}$$

In order to evaluate the theoretical formulation, error propagation from STA to the knee joint angles was additionally computed and compared with previously published error magnitudes. The joint angles were defined according to Grood and Suntay (1983). The error $\Delta\alpha$ of an angle α defined as

$$\cos\alpha = \mathbf{f}_1 \cdot \mathbf{e}_2 \tag{10}$$

was then given as

$$\Delta\alpha = \sqrt{\left(\frac{\partial\alpha}{\partial\mathbf{f}_1}\Delta\mathbf{f}_1\right)^2 + \left(\frac{\partial\alpha}{\partial\mathbf{e}_2}\Delta\mathbf{e}_2\right)^2}. \tag{11}$$

The error analysis was performed using the mathematical computing environment and programming language MATLAB (The MathWorks Inc., MA, USA).

3. Results

Both the knee joint angles and the modeled muscle-tendon lengths calculated from the reference kinematic data conform with the literature (Fig. 1). The analytical formulation led to estimated errors in the knee joint angles that were similar to those previously published (Table 1).