A Novel Muscle Element based on Arbitrary Lagrange-Euler (ALE) Description

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Multibody musculoskeletal models have enabled complex human movement simulation. Extensive range of studies have been performed on muscle element description. Up to now, almost all muscle-tendon units are defined as a nonlinear spring element (wired model) [1]. However, inertial effect is omitted in this model. Another drawback is that the nonlinear constitutive equation is derived based on small deformation assumption.

The alternative is using finite element (FEM) method. Conventional biomechanical FEM algorithm is based on Lagrange description. It is time-consuming due to fine grid and muscle-bone contact. To overcome this, a dynamic musculotendon element model is proposed in the framework of Arbitrary-Lagrange-Euler (ALE) description [2]. To describe the mass flowing medium with large movement and deformation, ALE description is embedded in two types of generalized coordinates. The Eulerian generalized coordinates are used for describing the lateral movement of muscles, and Lagrange ones for length variation.

Take a flexible knee musculoskeletal model as an example, shown in Fig. 1(a). Limb muscles are modeled as ALE elements on account of material softness and contact properties. The configuration of an element, as shown in Fig. 1(a)Fig. 1, is described by the position vector $\mathbf{r}$ and the arc-length parameter p. The governing equations of the element are obtained through the principle of virtual work, i.e.,

$$\mathbf{M}_e \ddot{\mathbf{q}}_e = \mathbf{Q}_P + \mathbf{Q}_f + \mathbf{Q}_E \tag{1}$$

where the generalized coordinates of a two-node element are $\mathbf{q}_e = [\mathbf{r}_1^T \quad \mathbf{r}_2^T \quad p_1 \quad p_2]^T$. Expressions for the mass matrix $\mathbf{M}_e$, the inertial force $\mathbf{Q}_P$ and the external force $\mathbf{Q}_f$ are the same as the ALE cable element shown in Ref [3]. The generalized elastic and damping force $\mathbf{Q}_E$ is derived from a Hill-type muscle model [4], depicted in Fig. 1(b)Fig. 1. It is composed of an active contractive force F_{CE} and a passive force F_{PE}. Here, the pennation angle α is simplified as a constant. The $\mathbf{Q}_E$ function can be obtained as

$$\mathbf{Q}_E = -\left(p_2 - p_1\right)\int_0^1 [(\frac{\partial \varepsilon}{\partial \mathbf{q}_e})^T \left(F_{CE} + F_{PE}\right)\cos\alpha]dp \tag{2}$$

Flexible musculotendon elements are fit for large displacement calculation. In the wired model, solving the equilibrium equation of muscle-tendon forces is time-consuming. Therefore, another approach is adopted: develop a passive tendon element and joint the muscle unit in series connection, shown in Fig. 1(c). Musculotendon equilibrium is directly solved by numerical integrator of the whole system without Newton-Raphson iteration in every substep. By this means, our numerical results have shown that large deformation has a non negligble effect on the former equilibrium equation. When muscle-tendon unit is stretched by 100% Green strain in isokinetic mode, muscle force $F_{mus}\cos\alpha$ is only 45.6% of tendon one F_{tendon} in the current configuration.

In addition, muscular path algorithms for the wired model can be transplanted to the ALE modeling approach. For the wired model, “Via-points” [5] and “wrapping surface” [6] algorithms are proposed in order to determine possible muscle paths. “Via-points” algorithms constrain the muscles to pass through imposed points. To accomplish this, a single ALE node is defined and attached to the imposed marker. It is testified by semitendinosus muscle, illustrated in Fig. 1(d)Fig. 2.

“Wrapping surface” algorithms realize modeling of certain muscles over geometrical entities during movement. For ALE muscle elements, wrapping geometry degenerates to a pulley, and it is fixed in the wrapping bone, shown in Fig. 1(e)Fig. 2. The geometric parameters of wrapping pulley is based upon bone anatomy together with the thickness of muscle/tendon. A single ALE node is pre-defined as the pulley-muscle tangent point. A cable-pulley joint is built as the position and tangent constraint. By this means, there is no need to define elements and contact pairs of muscles wrapping the pulley. The algorithm has been validated on a flexible multibody knee model for rectus fermoris muscles.

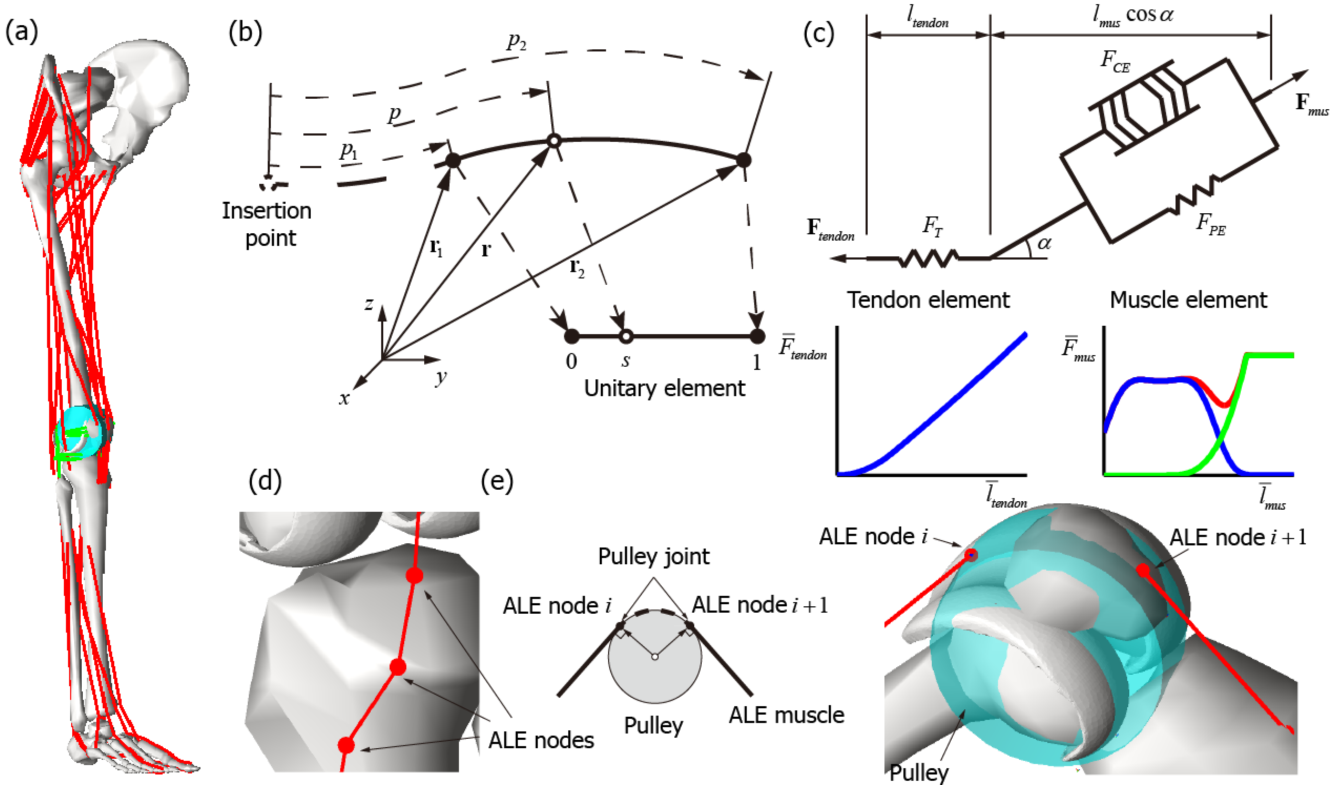

Fig. 1: Flexible muscle element based on ALE description. (a). The flexible knee model. Muscles are modeled as ALE muscle elements. (b). Schematic of a muscle element. (c). Schematic of musculotendon model. A Hill-type muscle model is implemented in the element; muscle and tendon elements are in series connection. (d) (e). Illustration of “Via-point” (d) and “Wrapping pulley” (e) algorithm.

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