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Automated muscle wrapping using finite element contact detection

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ABSTRACT

Realistic muscle path representation is essential to musculoskeletal modeling of joint function. Algorithms predicting these muscle paths typically rely on a labor intensive predefinition of via points or underlying geometries to guide wrapping for given joint positions. While muscle wrapping using anatomically precise three-dimensional (3D) finite element (FE) models of bone and muscle has been achieved, computational expense and pre-processing associated with this approach exclude its use in applications such as subject-specific modeling. With the intention of combining advantageous features of both approaches, an intermediate technique relying on contact detection capabilities of commercial FE packages is presented. We applied the approach to the glenohumeral joint, and validated the method by comparison against existing experimental data. Individual muscles were modeled as a straight series of deformable beam elements and bones as anatomically precise 3D rigid bodies. Only the attachment locations and a default orientation of the undeformed muscle segment were pre-defined. The joint was then oriented in a static position of interest. The muscle segment free end was then moved along the shortest Euclidean path to its origin on the scapula, wrapping the muscle along bone surfaces by relying on software contact detection. After wrapping for a given position, the resulting moment arm was computed as the perpendicular distance from the line of action vector to the humeral head center of rotation.

This approach reasonably predicted muscle length and moment arm for 27 muscle segments when compared to experimental measurements over a wide range of shoulder motion. Artificial via points or underlying contact geometries were avoided, contact detection and multiobject wrapping on the bone surfaces were automatic, and low computational cost permitted wrapping of individual muscles within seconds on a standard desktop PC. These advantages may be valuable for both general and subject-specific musculoskeletal modeling.

1. Introduction

Realistic muscle path representation is central to musculoskeletal system modeling, because muscle moment arms and lengths directly affect muscle force and moment production capacity, and finally joint contact forces (Dul et al., 1984; Herzog, 1992; Raikova and Prilutsky, 2001). However, our ability to measure or predict muscle path remains limited, particularly in joints like the glenohumeral joint with a complex anatomy and large range of motion.

Computer models can be automated to provide reliable prediction of moment arms over wide ranges of motion (Gatti et al., 2007). However, modeling becomes complicated when a muscle path deviates from a straight line as it wraps over surrounding anatomical features. Computerized approaches to muscle wrapping can be roughly classified into two categories, depending on the representation of the muscle and bone anatomies. In the first category, muscles are represented by deformable line segments. Here muscle segments are usually constrained to pass through via points (Delp and Loan, 1995) or, in the obstacle-set method, to wrap over simplified geometries approximating the centroidal muscle path (Charlton and Johnson, 2001; Garner and Pandy, 2000). Obstacle-set and via points have occasionally been combined (Holzbaur et al., 2005). These methods solve quickly and can deliver realistic moment arms. However, to provide valid predictions, the number and position of via points, or the appropriate obstacle type (sphere, cylinder, etc.), size, and orientation must be determined for each muscle segment at various joint positions. This becomes increasingly complex in joints with many muscles and multiple degrees of freedom.

In a second type of approach, wrapping has been achieved using precise numerical interfitting of bone and muscle anatomies. For instance, an earlier attempt was made to approximate the bone as a series of cross-sectional boundaries (Gao et al., 2002).

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This approach solved very quickly but necessitated substantial pre-processing to define the bony cross-sections and motion path delimiters. Later approaches have used sophisticated 3D volumetric finite element (FE) models to compute moment arms for certain lower limb muscles (Blemker and Delp, 2005). Here, many artificial boundary conditions (such as via points) were avoided by constraining the muscle within defined contact regions. This approach generally involves large computational expense and labor intensive data processing that could preclude its integration to larger musculoskeletal models (Blemker and Delp, 2005; Grosse et al., 2007; Marsden and Swailes, 2008; Vasavada et al., 2008). These limitations become overwhelming concerns when modeling the entire glenohumeral joint, where more than 20 muscles segments are regularly considered (Charlton and Johnson, 2006; Favre et al., 2005; Garner and Pandy, 2001; Holzbaur et al., 2005; Karlsson and Peterson, 1992a; van der Helm, 1994). Moreover, despite apparently higher "biofidelity", FE approaches have predicted moment arms that generally differ from experimental findings or from those obtained using other modeling methods (Blemker and Delp, 2005).

Thus existing numerical approaches for muscle path modeling involve a high degree of complexity and an extensive need for user intervention. This prevents their use in a more automatic fashion, severely limiting their utility for parametric joint studies or subject-specific modeling. In the via point and obstacle-set approaches, the complexity lies in representing the underlying guiding geometries, as well as implementing rules for wrapping and the associated algorithms for contact definition (Table 1). Furthermore, multiobject wrapping is often complicated by muscle penetration through bone (Audenaert and Audenaert, 2008; Charlton and Johnson, 2001; Marsden and Swailes, 2008; Marsden et al., 2008). In a volumetric 3D FE approach, the complexity lies rather in a computationally intensive modeling of the muscle. We hypothesized that multi-object wrapping on any shaped bone can be managed while avoiding a priori definition of via points or wrapping geometries by relying on automatic contact detection capabilities in commercial FE software. Further, by using a simplified muscle representation, we assumed that low computing costs would allow the model to solve quickly on a standard desktop PC. These advantages would be valuable in both general and subject-specific modeling, where efficient, flexible, and automatic multi-object wrapping is often required.

2. Methods

In the presented approach (Fig. 1), 3D bone surfaces are first oriented in a static position of interest. The muscles are modeled as a straight series of beam elements with very low bending stiffness. They are anchored at their insertion to the humerus with a predefined orientation, but not yet attached at their origin on the scapula. A wrapping step then displaces the muscle origin node toward its predefined origin on the scapula. Along the way, the muscle elements wrap around relevant bone surfaces, relying on contact detection of the FE software. This sequence can later be repeated for any joint position and can be implemented incrementally to simulate motion as a series of static positions.

Geometries of the humerus and scapula were imported from the *Bel repository* (Van Sint Jan et al., 2004) into Geomagic Studio 8 (Geomagic, Inc., Research Triangle Park, NC, USA). From the initial triangulated surface mesh, a smoothed NURBS surface was created for each bone using the *autosurface* function with default parameters. These surfaces were imported as rigid bodies into Marc Mentat 2007r1 (MSC.Software, Santa Ana, CA). A 24 mm radius was estimated by fitting a sphere to the humeral head (Meskers et al., 1998), which falls within reported values for average adult shoulders (Boileau and Walch, 1997; Iannotti et al., 1992). The coordinate system for both bones and their relative position in the joint was defined according to ISB recommendations (Wu et al., 2005). The humeral head rotation center (found by sphere fitting) was positioned with respect to the scapula by linear regression (Meskers et al., 1998). The humerus was oriented relative to the scapula in the joint configuration of interest by rotating around this point (Meskers et al., 1998; Veeger, 2000), assuming a fixed rotation center.

All muscles crossing the glenohumeral joint were considered. The teres major, coracobrachialis, triceps, biceps short and long head were each modeled with one segment. The rotator cuff muscles were represented using two supraspinatus, three infraspinatus, three subscapularis, and two teres minor segments. The latissimus dorsi and the pectoralis major were each composed of three segments and the deltoid was divided into six segments (one anterior, three middle, and two posterior segments). Each muscle segment was modeled as 150 deformable, two-node, straight, elastic beam elements in series (Element number 98, (MSC.Software)).

Origin and insertion sites for each muscle segment were identified on the bone surface contours as described in previous studies (Favre et al., 2005, 2009a). Each attachment footprint was divided into equal parts according to the number of muscle segments. Typically, if the muscle was segmented into medial and lateral segments, the medio-lateral width of the attachment area was halved, and each segment was first positioned to attach at the respective center of the subarea. The exact origin and insertion sites, not being known in advance, were varied within the designated muscle attachment footprint until a suitable agreement was reached with experimentally reported moment arms. All origin and insertion coordinates are listed in Table 2.

After each segment was attached to the humerus at its insertion site, the initial segment orientation was set as perpendicular to the humeral surface with the joint in the resting position. In a few cases, the default segment orientation was adjusted to avoid non-physiological bone surface contact during the wrapping process. Here, the humerus was rotated to the end of the physiological range of motion in axial rotation (Rundquist and Ludewig, 2004) and elevation (limited by inferior and superior impingement). If a prewrapped muscle segment was seen to penetrate the scapula, or would later obviously wrap on an inappropriate bone surface, the segment was rotated backward in the plane of motion until the problem disappeared. For the infraspinatus and teres minor, which insert close to the glenoid border, adjustment of initial orientation was necessary to prevent scapula penetration in extreme external rotation. The posterior deltoid was similarly adjusted to avoid contact in external rotation. All other segments were left in their perpendicular orientation. All initial orientation vectors are shown in Table 2. Once set, the same pre-wrapping orientation relative to the reference coordinate system was utilized for all subsequent wrapping simulations, regardless of joint position. To assess sensitivity to initial orientation, both supraspinatus segments were systematically re-oriented 10° from the default orientation towards the medial, lateral, anterior and posterior directions. The change in moment arm and muscle length was monitored during scapular elevation from 0° to 80°, and then averaged.

Insertion nodes were constrained to prohibit translations, but allowed three degrees of freedom in rotation. The free end node of each segment was then moved along the shortest Euclidean distance towards its designated point of origin on the scapula. Contact between the bone surface and the muscle nodes were defined. Non-physiological muscle wrapping on the acromion and coracoid process was avoided by removing them from the scapula contact body, allowing the muscles to penetrate these structures when wrapping. During simulations the muscle nodes were automatically controlled for contact with the bone surface. The muscle segments deformed and wrapped automatically on contacting bone surfaces. A glued node constraint between the contacting muscle-bone nodes restricted relative tangential motion after contact. This prevented muscle drift on the bone during the wrapping process for a given static joint position of interest.

Muscle moment arms were computed at 95% completion of the wrapping process, slightly shifting the muscle origin from the bone surface (Bremer et al., 2006; Favre et al., 2005, 2008, 2009a). The vector from the last muscle node in contact with the bone (automatically detected using the contact status option (MSC.Software)) to the tenth node towards the origin defined the muscle line of action. The moment arm was computed as the perpendicular distance from this vector to the humeral head center. A Matlab routine (v.7.0.1, The MathWorks, Natick, MA, USA) automated the entire procedure and calculated muscle wrapping for incrementally applied changes in joint position.

The method was validated against published experimental data of shoulder muscle lengths (Holzbaur et al., 2007; Klein Breteler, 1996; Langenderfer et al., 2004; Veeger et al., 1997) and moment arms (Favre et al., 2005; Hughes et al., 1998; Kuechle et al., 1997; Kuechle et al., 2000; Langenderfer et al., 2006; Liu et al., 1997; Nyffeler et al., 2004; Otis et al., 1994; Poppen and Walker, 1978). The moment arms were computed over a series of discrete joint positions in 10° increments to describe the corresponding experimental motion. Muscle segment length was calculated as the summation of individual element lengths in the joint rest position (0° elevation, neutral axial rotation).

Finally, moment arms of the rotator cuff muscles in two joint positions were compared with previous modeling results (Charlton and Johnson, 2006; Dickerson et al., 2007; Garner and Pandy, 2000; Holzbaur et al., 2005; van der Helm, 1994; Webb et al., 2007).

3. Results

Wrapping for a given joint position was determined within 10 s for single muscle segments and in less than 4 min for 27