Modelling of the Shoulder Mechanism

A report describing the development of a three-dimensional biomechanical model of the human shoulder complex.

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Abstract

Biomechanical models of the human body are important tools in understanding the functional principles of human movement and coordination. This paper describes the development of a three-dimensional model of the human shoulder complex using the inverse dynamics modelling system *AnyBody* (http://anybody.auc.dk/). The model contains four bones, together with four articulating joints and thirty-six muscle elements, representing twenty-one anatomical muscles. Bones are modelled as rigid segments, joints as spheres and muscles as stretched strings between origin and insertion points. The connection between the scapula and the thoracic wall is also regarded as a joint and the individual orientation of the scapula is defined from this point. An investigation towards the application of this model for the optimal design of muscle specific exercise equipment is then described.

1.0 Introduction

1.1 The *Anybody* System

An interpretation of human movement is difficult to achieve without dynamic biomechanical simulations of the joints and muscles of the body. The *AnyBody* system performs kinematic analysis of human movements and identifies individual muscle actions, joint loads, tendon elasticity, mechanical and metabolic work, and many other characteristics of the active human body. The system is based on inverse dynamics, where the motion and external forces are used as input, to allow computation of muscle forces and joint reactions. The equilibrium equations are formed but the system is statically indeterminate because there are more muscles spanning each joint than there are degrees of freedom. To overcome this problem the system distributes muscle loads according to a minimum fatigue criterion leading to a min/max problem of muscle forces with the equilibrium equations as constraints.

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Due to its numerical efficiency, *AnyBody* is also capable of optimising inputs such as the dimensions of the mechanism, the motion performed, or the exterior load variation. The system therefore becomes a useful tool in the design of exercise machines and other ergonomic equipment, where the analysis involves both the mechanics of the machinery and the physiological movements of the human body.

1.2 Prior Studies

The first mechanical shoulder models were proposed at the end of the 19^{th} century and involved replacing the muscles of cadaver shoulder specimens with hemp threads. These models were used to define shoulder joint positions and to record the resulting change in the displacement of various muscles.

Later models of shoulder motion modelled the mechanism in two dimensions only. These studies were merely describing the motion of the humerus with respect to a non-moving scapula. (DeLuca and Forrest, 1973; Dul, 1987; Poppen and Walker, 1978). The models were extensively oversimplified and did not provide a realistic interpretation of the motion of the shoulder.

Wood et. al. (1989) digitized the anatomy of the shoulder and elbow muscles and calculated trajectory data for each muscle to create a prosthetic limb control scheme.

Karlsson and Peterson (1992) determined shoulder muscle activity by computation of anatomical data.

A complete dynamic shoulder model was then suggested by Van der Helm (1994) by means of a dynamic finite element method. The bones were modelled as rigid segments connected by three-dimensional hinge elements and the scapulo-thoracic joint was modelled as a triangular structure constrained in contact on an ellipsoid. The finite element method assumes that the deformation modes of the elements are expressed as a function of the displacement of its end nodes.

Other detailed three-dimensional models have been presented in a series of papers (Hogfors et al, 1987,1991,1995; Peterson 1994; Siemienski et al., 1995.). These models rely heavily on observations that in the shoulder there are strong inter-individual similarities in motion as well as muscle recruitment patterns.

2.0 The Biomechanical Model

2.1 Human Upper Arm Anatomy

2.1.1 Skeletal Structure

The shoulder girdle consists of a closed-linked kinematic chain of bones that connect the upper arm to the trunk. The four bones included in the shoulder complex are the thorax, clavicle, scapula and humerus. These bones are modelled as rigid segments between the following articulating joints.

1. Sterno-clavicular joint (SC) which articulates the clavicle by its proximal end onto the sternum.
2. Acromio-clavicular joint (AC) to articulate the scapula by its acromion onto the distal end of the clavicle.
3. Gleno-humeral joint (GH) which allows the humeral head to rotate in the glenoid fossa of the scapula.

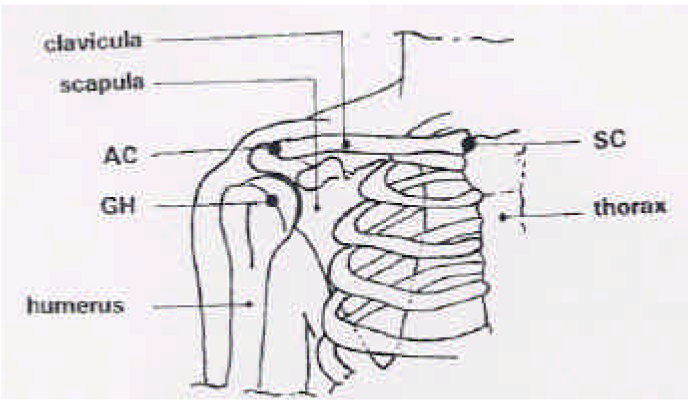

Figure 1: The joints and segments of the shoulder complex. (Breteler et al., 1999)

The gleno-humeral joint has been modelled as a spherical joint, while the acromio-clavicular and sterno-clavicular joints have been modelled as three orthogonal hinge joints, functionally known as a universal joint. This arrangement allows the angles between these two joints to be quantified in the system and the three dimensional movement of the clavicle controlled.

In order to achieve realistic shoulder motion, the scapula has been constrained to rotate on a spherical joint. This joint has been ground at a position in front of the thorax from which a realistic scapulo-thoracic motion can be described. Currently the shoulder rhythm[1] (Hogfors et al., 1991), has not been taken into consideration in the model and the motion of the scapula is driven separately to the humerus. This movement has been arbitrarily defined with reference to available graphic visualisations, (Maurel et al., 1999) but from the joint configuration the scapula is assumed

[1] The shoulder rhythm describes the way in which the humerus elevation is composed of rotations of the gleno-humeral joint and movements along the scapulo-thoracic gliding plane.

to glide on the surface of a sphere. It is anticipated that in the near future a description of the shoulder rhythm will be possible in the *Anybody* system.

2.1.2 Musculature

Twenty-two muscles serve the shoulder mechanism and together provide the complex motions of the human upper limb. The majority of the muscles of the shoulder are broad and have no unique line of action and for modelling purposes those with large attachment sites have been split into several elements in accordance with Makhsous, 1999. Thirty-six muscle elements have been modelled in the system, representing twenty-one anatomical muscles. The muscle parameters used as input to the system include the physiological cross sectional area (PCSA), fibre length and tendon length (please refer to Appendix A).

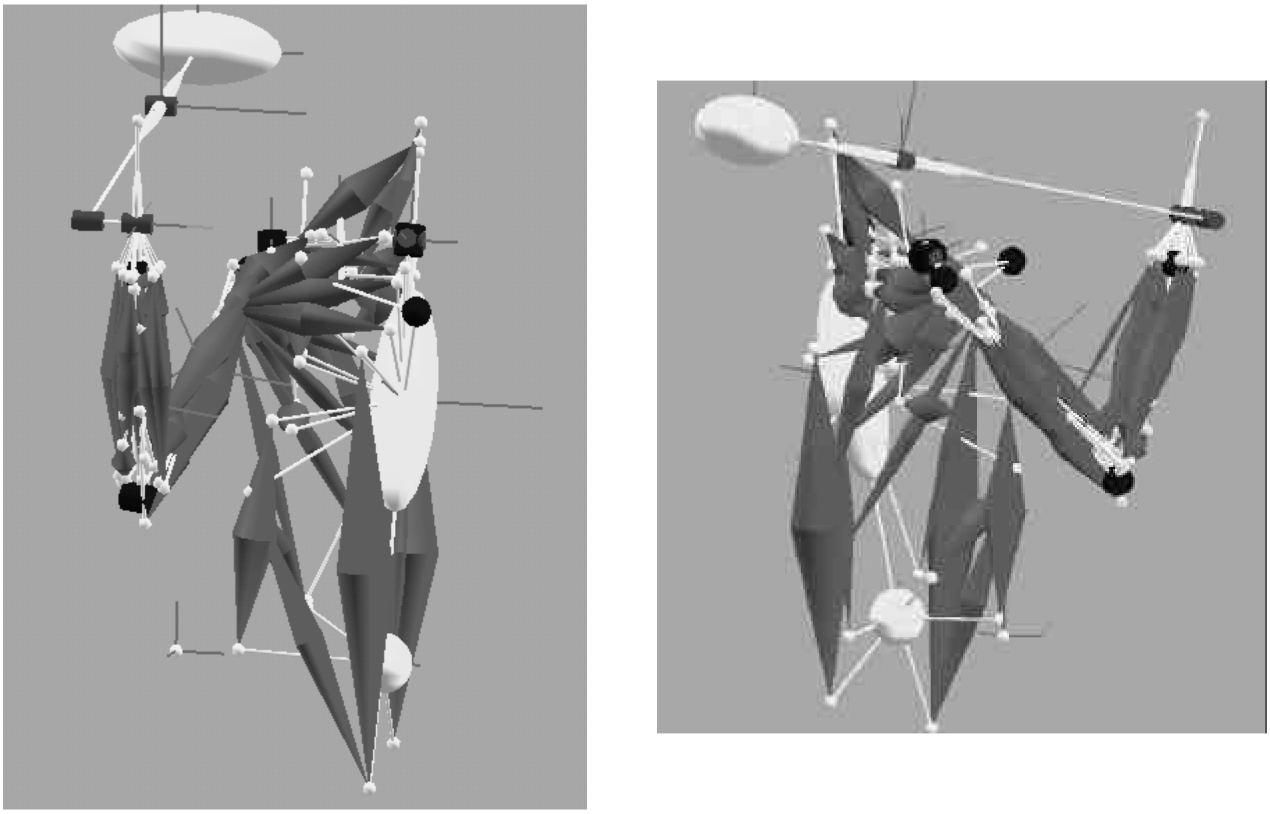

Figure 2: Graphic representation of the shoulder muscle including joints, segments and muscle elements.

Literature reporting musculo-tendon lengths in the shoulder girdle was found to be scarce and it was necessary for some muscle parameters to be assumed from data reporting natural muscle length. Adjustments to these values were made to allow reasonable muscle ratios to be achieved by the system.[2]

The muscles are modelled as stretched strings between origin and insertion and the muscle forces are assumed to act along these direct lines of action. Many of the muscles of the shoulder complex follow the contours of bony structures however, and would be better modelled as curved elements

[2] A reasonable muscle ratio was assumed to be between 0.5 and 1.5 during motion.

(Van der Helm, 1994). It is anticipated that further development of the model in this area will occur in the near future to fulfill this requirement. The affected muscles include the *latissimus dorsi*, *pectoralis major*, *serratus anterior*, posterior and anterior parts of the *deltoid*, *infraspinatus*, *subscapularis*, *supraspinatus* and the *biceps brachii* (long head).

The muscle forces are restricted to range from zero to a maximum value that is assumed to be in proportion to the PCSA of the muscle. The indeterminate system is then optimised by the use of several objective functions that have been built into the *Anybody* system. The idea of optimisation is based on the assumption that forces between different shoulder muscles are distributed consistently in similar tasks.

2.1.3 Preliminary results

Without validation of the muscle force predictions against EMG recordings it is difficult to predict the reliability of the output from the prescribed shoulder model. However the preliminary results appear promising and the force predictions yielded are within the limit of maximum muscle forces that have been documented in literature. (Makhsous, 1999)

The motion the model currently undergoes is in simulation of a Seated Overhead Shoulder Press. This movement involves at a primary level the use of the *triceps brachii* and the deltoids as well as *teres major* and the muscles of the rotator cuff, namely *supraspinatus*, *infraspinatus*, *teres minor* and the *subscapularis*. Currently the *deltoid* muscles and the *triceps brachii* exhibit only small loads, this is possibly due to the fact that the elements are modelled as strings and do not wrap around the respective bone contours of the gleno-humeral and elbow joints. The reliability of the assumed muscle parameters is questionable and is considered a large source of inaccuracy in the model.

3.0 Optimal Design

The development of a biomechanical model of the shoulder, together with the optimization capabilities available in the *Anybody* system, allows for the analysis and design of exercise equipment which can strengthen the upper limb. Training and strengthening the muscles that surround the gleno-humeral joint is important to maintain its stability, particularly in athletes involved in sports in which circumduction is the main action. This includes activities such as the pitching motion in softball or the motion involved in backstroke swimming as well as all other ‘throwing’ sports.

Relieving joint and ligament forces is often very important for rehabilitation purposes, especially for injuries involving the muscles of the rotator cuff (Mantone et al., 2000). Identification of a movement and loading situation which minimises the gleno-humeral joint reaction force whilst maximising muscle activity to maintain its stability is possible to determine using the *Anybody* system. This is effectively the problem of design of an exercise machine for the shoulder girdle that has all the characteristics of a classic engineering design problem:

- It has a finite number of variables describing the overall design of the mechanism.
- Its design must meet a number of requirements such as the motion range or limitation of the load on joints or other fragile elements of the body.

- Depending on the purpose of the training, a number of desirable qualities are available as candidates for objective functions.
- The development of a biomechanical model of the shoulder has allowed for the description of movements that target specific muscles in the shoulder and the possible development of an exercise machine to strengthen these muscles.

The use of the shoulder model for this purpose is currently being investigated.

4.0 Conclusion

Without validation of the developed shoulder model it is difficult to postulate on the success of the model in terms of a reliable physiological interpretation of shoulder function. However, this work is considered an important step in the process of creating a model, which is a useful tool in the assessment of loads on the human shoulder. The model is currently limited by the fact that the constraints imposed by the shoulder rhythm are not implemented in the system and the musculo-tendon parameters have been assumed for most muscles. The model can be used to identify a motion which minimises the reaction force at the gleno-humeral joint whilst strengthen the rotator cuff muscles and in the future will be used to optimally design an exercise machine which facilitates this movement.

5.0 Acknowledgements

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Appendix A

No.	Muscle	PCSA (cm^2)	Ref.	Fibre Length OIL (cm)	Tendon Length Lm (cm)	Ref.
1	Sternocleidomastoid	1.0	1	0.2	0.185	A.V
2	Omohyoideus	1.0	1	0.092	0.085	A.V
3	Latissimus Dorsi A	1.72	1	0.22	0.14	A.V.
3	Latissimus Dorsi B	1.72	1	0.27	0.14	A.V
3	Latissimus Dorsi C	1.56	1	0.35	0.14	A.V
3	Latissimus Dorsi D	1.56	1	0.33	0.14	A.V
4	Pectoralis Major A	4.52	2	0.15	0.10	A.V
4	Pectoralis Major B	4.07	1	0.175	0.10	A.V
4	Pectoralis Major C	4.07	1	0.19	0.10	A.V
5	Pectoralis Minor	2.74	1	0.122	0.09	A.V
6	Levator Scapulae	2.83	2	0.09	0.085	A.V
7	Trapezius A	4.72	1	0.127	0.07	A.V
7	Trapezius B	9.57	1	0.099	0.06	A.V
7	Trapezius C	2.58	1	0.162	0.8	A.V
8	Rhomboid Minor	3.23	3	0.101	0.05	A.V
9	Rhomboid Major	3.87	3	0.10	0.05	A.V
10	Serratus Anterior A	5.47	1	0.093	0.073	A.V
10	Serratus Anterior B	3.57	1	0.124	0.09	A.V
10	Serratus Anterior C	3.76	1	0.093	0.07	A.V
11	Deltoid A	4.29	1	0.11	0.05	A.V
11	Deltoid B	7.42	1	0.06	0.05	A.V
11	Deltoid C	8.84	1	0.17	0.16	A.V
12	Subclavius	1.0	1	0.05	0.048	A.V
13	Teres Major	8.49	1	0.12	0.10	A.V
14	Teres Minor	2.075	3	0.08	0.07	A.V
15	Coracobrachialis	2.51	2	0.11	0.075	A.V
16	Infraspinatus A	6.37	1	0.12	0.075	A.V
16	Infraspinatus B	7.67	1	0.09	0.04	A.V
17	Subscapularis A	2.83	2	0.11	0.07	A.V
17	Subscapularis B	5.10	2	0.14	0.07	A.V
18	Supraspinatus	3.9	3	0.10	0.05	A.V
19	Biceps Brachii	5.0	3	0.32	0.17	3
20	Triceps Brachii Caput Longum	5.3	3	0.29	0.102	3
20	Triceps Brachii Caput Mediale	4.7	3	0.15	0.063	3
20	Triceps Brachii Caput Lateral	4.7	3	0.235	0.084	3
21	Brachialis	5.3	3	0.125	0.105	C.V

Note: A.V. – Assumed Value
C.V. – Calculated Value

References:
1. Siemienski et al., 1995
2. Veeger et al., 1992
3. Yamaguchi et al., 1990