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Modelling of the human shoulder as a parallel mechanism without constraints

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ABSTRACT

The synthesis of shoulder kinematics, either for simulation in a model or imitation in a robot, is a challenging task because of the contact between shoulder blade and ribcage. As the shoulder moves, the shoulder blade glides over the ribcage. In kinematic models used to predict musculoskeletal kinetics, the contact is included using equality constraints, creating interdependencies between the kinematic coordinates. Such interdependencies make motion planning complex. Robotic mechanisms often imitate the shoulder's end-effector kinematics but not the gliding shoulder blade architecture. It is only recently that a gliding shoulder blade architecture has been mechanically achieved. The goal of this paper is to propose a novel kinematic parallel model of the shoulder that includes the contact without using constraints. Mechanically, the gliding architecture is replaced with a parallel architecture. A shoulder model with constraints is used to build the parallel model. It is shown that replacing the contact constraints with kinematically equivalent kinematic chains, leads to a 2–3 parallel platform model of the shoulder. The scaffold model and parallel model parameterisations of the shoulder's kinematics are analysed in terms of the forward kinematic map. The coordinate spaces of the kinematic maps are analysed, resulting in three minimal parameterisations. Each minimal parameterisation uses a set of coordinates equal to the number of degrees of freedom. The minimal coordinates are independent and considerably simplify motion planning.

1. Introduction

The shoulder's role in our daily interactions with our environment is essential and dysfunctions can be severely debilitating. As such, a considerable amount of research has been done on the shoulder, including musculoskeletal modelling for simulation purposes in clinical contexts [1–3]. The human shoulder is also a highly flexible system capable of supporting heavy loads and has a wide range of movements. Given these attractive characteristics, it has also been studied for the purposes of imitation in

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humanoid robots [4,5,6]. However, the shoulder remains a challenging system for a number of reasons, such as its kinematic complexity.

The shoulder can be considered as a parallel mechanism [7,8]. The motion of the shoulder girdle with respect to the thorax results from the combined movement of three bones: The clavicle (collar bone), scapula (shoulder blade) and humerus (upper arm bone). The bones are serially connected together through three articulations, yielding a kinematically redundant system. Multiple configurations of the bones yield the same configuration of the elbow joint. This characteristic is what gives the upper limb such a vast workspace. The shoulder is a parallel mechanism because there is a contact between the scapula and thorax, called the scapulothoracic contact. It is not an articulation but is important kinematically as it guides the movement of the scapula relative to the thorax, reducing the number of degrees of freedom of the shoulder. Unlike the other three articulations, the scapulothoracic contact cannot be characterised by a single kinematic pair and is challenging from a modelling perspective [6,9]. Many musculoskeletal models parameterise the kinematics using joint angles and enforce the scapulothoracic contact with equality constraints [7,1,10,11]. The presence of constraints in the kinematic model limits the options for motion planning which is a crucial step in predicting musculoskeletal kinetics, one of the main purposes of musculoskeletal shoulder models. Solutions to the motion planning procedure are data-driven optimisation [12,13] or regression models of the clavicle and scapula's kinematics in terms of humeral kinematics [14–16]. Optimisation procedures require measuring kinematics on the real system which is a challenging task [17,18] and regression models do not respect the constraints. The scapulothoracic contact is also challenging from a robotics perspective. Given the shoulder's large workspace and load bearing capabilities, a number of robotic systems have been developed, using serial [19] and parallel [4] architectures to try and reproduce the shoulder's kinematics. However, it is only recently that robots have been developed, incorporating the scapulothoracic contact [20,21]. Indeed, the technology to build such robots, like smaller motors and efficient pneumatic artificial muscles, has only recently been developed [22]. In addition to the complexity of the scapulo-thoracic contact, there is a coordination between the movement of the scapula and humerus [23], called the scapulohumeral rhythm that is not easily reproduced. Thus, the shoulder's kinematics still present a serious challenge of synthesis for simulation purposes and reverse engineering.

The goal of this paper is to present a model of the shoulder that incorporates the parallel architecture without explicitly using constraints. The presentation is based on a detailed kinematic analysis of a model of the human shoulder, combining mathematical rigour and anatomical accuracy. The proposed model is built from a kinematic model of the shoulder parameterised by joint angles [24], considering the bones to be rigid bodies, the articulations to be ideal mechanical joints and represents the contact between scapula and thorax using two holonomic constraints. The model has seven degrees of freedom: nine kinematic coordinates subject to two equality constraints and is referred to as the natural kinematic model. The proposed model is constructed by replacing the constraints with kinematic chains, leading to an equivalent parallel mechanism description of the shoulder. These chains are parameterised with additional coordinates providing three alternative forward kinematic maps. The natural kinematic map and two others. The coordinate space topologies of all three maps are analysed, resulting in the definition of three different minimal parameterisations of the model's kinematics, each using seven independent coordinates. The paper concludes with a short discussion on the limitations of the model and the possible applications of the kinematic analysis.

2. A kinematic shoulder model

2.1. Geometric model

This section presents the kinematic shoulder model from which the parallel model is constructed. The model is similar to other models from the literature in its definition of reference frames and coordinates [7,1]. The present model parameterises bone movement relative to the thorax which is fixed (see [25] for anatomical references. Fig. 1). Each bone is represented by three points. The thorax is presented by four points, yielding a total of 13 points, defined in the following list:

1. IJ: Jugular Inscision, top of the sternum (thorax),
2. PX: Xyphoid Process, bottom of the sternum (thorax),
3. T8: Eighth thoracic vertebrae (thorax),
4. C7: Seventh cervical vertebrae (thorax),
5. CN: Conoid ligament attachement point (clavicle),
6. SC: Sternoclavicular articulation centre (clavicle),
7. AC: Acromioclavicular articulation centre (clavicle),
8. AA: Angulus acromialis (scapula),
9. TS: Trigonum Spinae (scapula),
10. AI: Angulus Inferior (scapula),
11. GH: Glenohumeral articulation centre (humerus),
12. EL: Lateral epicondyle of the humerus (humerus),
13. EM: Medial epicondyle (humerus).