# Multibody modelling of ligamentous and bony stabilizers in the elbow joint

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***Abstract*—The elbow ligamentous and bony structures play essential roles in the joint stability. A predictive tool of the joint behaviour after the loss of retentive structures would be helpful in designing reconstructive surgeries and in pre-operative planning. In this work, a multibody model consisting of bones and non-linear ligamentous structures is presented and validated through comparison with experimental data.**

***Keywords*—elbow, multibody, ligaments, MCLC**

## I. Introduction

THE elbow joint comprises ligamentous and bony stabilizers that furnish both primary and secondary stability during flexion. At 20°-120° degrees of flexion, the elbow stability is dependent on medial collateral ligament complex (MCLC), which is composed of three ligamentous structures: Anterior Bundle (AB), Posterior Bundle (PB) and Transverse Bundle (TB). TB is commonly considered not involved in the elbow stability [1]. The undisputed importance of the AB as a primary stabilizer of the elbow to valgus stress was deeply investigated, and, up to present days, in simple unstable or complex dislocations the reconstruction techniques addresses the AB only [2]. Although the PB role in elbow stability has not been clearly defined yet, it is always injured in dislocated elbows and it is sacrificed in many common surgical procedures. Anyhow, any reconstruction procedure aims at the restoration of the original joint stability, and since ligaments stabilizing tensions change with the motion, a thorough knowledge of osseous interactions and ligaments function is necessary. However, an exhaustive experiment into the ligament constraints changes in relation to joint motions would be time consuming. An advantageous solution would be the use of computational modelling, that has become an important tool for the characterization of complex systems. Moreover, validated models can be used to investigate and optimize surgical procedures in a virtual setting.

The purpose of this study was to develop an anatomically detailed elbow joint multibody model provided with non-linear ligaments. The model performances were evaluated through comparison between the model kinematics and experimental measurements collected from literatures.

## II. Materials and Methods

A multibody model was created in ADAMS (MSC Software Corporation, Santa Ana, CA) by importing the CAD geometries of humerus, ulna and radio, pre-assembled in the extended position. A density of 1600 kg/m$^3$ was used for the osseous components [3].

### A. Ligaments formulation

The model comprises the ligament complexes involved in the elbow joint: medial collateral ligament complex (MCLC), lateral collateral ligament complex (LCLC), radial collateral ligament (RCL) and interosseous membrane (IOM), as listed in Table I. Both localization (Figure 1) and ligaments stiffness (Table I) were obtained through anatomic and biomechanical data found in literature.

TABLE I
Ligaments stiffness

| *ID* | *Tissue bundle* | *Ligaments* | *Stiffness K (N/mm)* |
|---|---|---|---|
| A-a | MCLC | Anterior AB | 36.15 |
| B-b | [4] | Posterior AB | 36.15 |
| C-c | | Anterior PB | 26.00 |
| D-d | | Posterior PB | 26.00 |
| E-e | LCLC | Anterior RCL | 23.25 |
| F-f | [4] | Posterior RCL | 23.25 |
| G-g | | Ulnar | 57.00 |
| N-n | | Anterior Annular | 57.00 |
| P-p | | Posterior Annular | 57.00 |
| O-o | DRULs | Dorsal | 13.20 |
| H-h | [5] | Palmar | 11.00 |
| I-i | IOM | Oblique cord | 65.00 |
| M-m | [6]-[8] | Proximal Accessory band | 18.90 |
| L-l | | Distal Accessory band | 18.90 |
| K-k | | Proximal Central band | 65.00 |
| J-j | | Distal Central band | 65.00 |

Ligaments and intraosseous membrane were then modelled as non-linear springs thanks to the implementation of user define functions (Eq. (1)) describing the load–strain relation.

$$Load = \begin{cases} 0 & \varepsilon < 0 \\ -\dfrac{1}{4}K\dfrac{\varepsilon^2}{\varepsilon_L} & 0 \le \varepsilon \le 2\varepsilon_L \\ -K(\varepsilon - \varepsilon_L) & \varepsilon > 2\varepsilon_L \end{cases} \quad (1)$$

The stiffness parameters K for each bundle are summarized in Table I, while the spring parameter $\varepsilon_L$ was assumed to be 0.03. A parallel damper with a damping coefficient of 0.5 Ns/mm was also added to the formulation [9].

### B. Articular contact

Humerus-ulna, humerus-radio and ulna-radio contact forces were defined through an impact formulation (Eq. (2)) describing the contact force $F_c$ as a function of the interpenetration between bodies ( $\delta$ ) and the interpenetration velocity ( $\dot{\delta}$ ).

$$F_c = k\delta^e + c(\delta)\dot{\delta} \quad (2)$$

*k* is the contact stiffness (8000 N/mm), *e* is the nonlinear power exponent (equal to 2) and *c* is the damping coefficient (400 Ns/mm). An additional parameter *d* (0.001 mm), embedded in the $c(\delta)$ function, limits the interpenetration to a maximum value [10], [11].

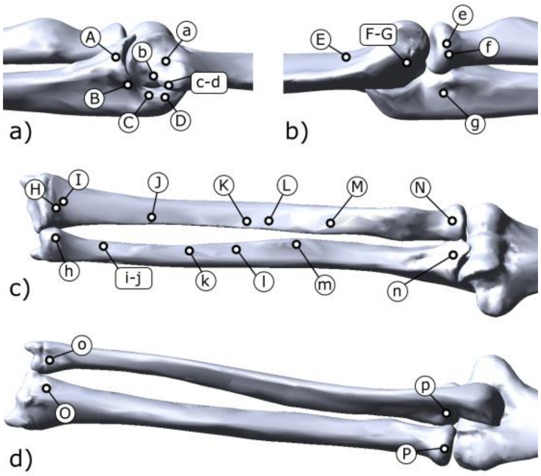


**Figure 1. Ligaments insertions in the medial view (a), lateral view (b), top view (c) and bottom view (d). Uppercase and lowercase letters are referred to ligaments listed in Table I**

### *C. Maneuvers setup*

To validate the model the experimental maneuvers performed by Gluck et al. [12] and Golan et al. [13] were recreated at 30°, 60° and 90° of flexion, imposing an axial compression along the ulnar axis (10 N [12] and 25 N [13] respectively), with varus (5°) and internal rotation moments (2.5 Nm). To recreate the experimental conditions of Gluck's work, a coronal cutting model has also been introduced (Fig. 2). A set of markers were placed on the medial side of the elbow joint to measure the distal (I-III) and proximal (I-IV) openings. Results were compared to the experimental outcomes [12], [13].

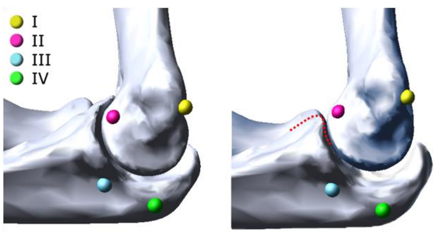


**Figure 2. Markers placement in intact (left) and cut coronoid model (right): I-III is the Distal Gap while I-IV is the Proximal Gap**

## III. Results and Discussion

Simulations results in each loading condition are summarized in Table II. The proximal gap was found to be the largest in each simulation condition, and both distally and proximally the coronoid cut leads to an increased gapping at all flexion degrees, as found in Gluck's work. Also in Golan's manoeuvre an increase in distal and proximal gap was obtained, even if the gapping was smaller in size because of the coronoid presence. Previous studies of the MCLC highlighted an increasing PB activation from mid to full flexion, suggesting that the absence of the PB most influences the stability of the articulation at higher flexion degrees [1], [4]. However, the coronoid engaging at high angles increases the elbow stability even in absence of the PB.

TABLE II
Distal and proximal gap in the Gluck's and Golan's maneuvers

| | *Flexion Degree* | *30°* | | *60°* | | *90°* | |
|---|---|---|---|---|---|---|---|
| | *Gap [mm]* | *Dist.* | *Prox.* | *Dist.* | *Prox.* | *Dist.* | *Prox.* |
| [12] | Intact elbow | 1.08 | 3.05 | 1.94 | 3.67 | 0.74 | 2.50 |
| | PB and Coronoid cut | 4.95 | 8.76 | 4.29 | 7.18 | 3.77 | 7.64 |
| [13] | Intact elbow | 1.25 | 3.44 | 1.92 | 3.63 | 0.73 | 2.51 |
| | PB cut | 1.28 | 3.46 | 2.06 | 3.75 | 2.19 | 4.58 |

The high similarity between the model results and the experimental measurements suggests the capabilities of the multibody framework in the quantitative evaluation of anatomical and physiological parameters. Furthermore, huge advantage of the multibody model is the possibility to investigate a potentially infinite number of configurations (ligaments ruptures and/or reconstructions), avoiding the need for many elbow samples and greatly reducing costs. Therefore, the rigid body modelling of complex anatomic and physiologic structures turns out to be a promising predictive tool and the potential applications in the pre-operative planning and surgical technique optimization are significant.

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