Development and Experimental Validation of a Computational Model of the Elbow Joint

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Disclosures:

Introduction: Computational models of human musculoskeletal systems are a valuable tool for studying the biomechanics of movement. In comparison to in-vitro experiments, computational models offer the promise of reducing time and costs, and can provide complimentary data to experimental tests[1]. Computational models also provide the ability to perform parametric analyses by easily and iteratively varying any parameter such as dimension, force, joint angle, etc. This ability can be invaluable in the evaluation of joint implant design. For example, the effects of altering any implant feature can easily be evaluated by virtually altering that feature. This includes factors related to the surgical implantation procedure, such as implant positioning. However, the complexities of a musculoskeletal joint requires that many assumptions be made to achieve a working computational model. To date, no such model of the elbow has been validated using experimental data. Thus, the purpose of this study was to develop a computational elbow joint model and to validate it using a well-established in-vitro elbow motion simulator[2]. A clinically relevant condition of radial head implant length[3,4] was also evaluated in a phantom model both experimentally and computationally.

Methods: A phantom elbow model was designed using a linked ulnohumeral implant and a radial head implant (Latitude Total Elbow Arthroplasty, Tornier Inc.). These components of known geometry were used in order to generate a perfectly matching computational joint geometry from CAD models. The size, forearm center of mass and muscle attachment sites were designed based on the 50th percentile male[5-7]. To further simplify the model, collateral ligaments and secondary stabilizers were not simulated. The major muscular contributors to elbow motion (i.e. biceps, brachialis and triceps) were simulated, by using braided Dacron® cable to connect tendon attachment sites to the apparatus’ servo motors. The radial head could be adjusted from its nominal position to lengthen or shorten the radius.

The computational model was developed within the LifeMOD™ software package. The computational model aligns with the phantom limb in terms of dimensions, mass and function. Tendon wrapping was also incorporated into the computational model to accurately depict the muscles lines of action. The muscle forces needed to flex the phantom limb were recorded using the in-vitro testing apparatus and compared to the computational model (Figure 1).

Two studies were performed within this investigation. Study 1: The experimental and computational models were tested in three different gravity loading positions which included vertical, varus, and valgus. Flexion from 0 to 120 degrees was simulated in all three positions. Intra-class correlation (ICC) with absolute agreement was used to compare the muscle forces between the computational and experimental models. Study 2: The effects of lengthening or shortening the radial head on muscle forces was investigated using the experimental and computational model in the valgus position. The valgus position was chosen as radial head height is most influential in this position. The radial head was positioned at three different heights(shortened, nominal, lengthened), and the muscle forces required to flex the phantom limb were recorded. The triceps was held to a constant 15 N in this study at the different radial head heights. ICC’s were used to evaluate correlations of the biceps and brachialis muscle forces at the three different levels of radial head position.

Results: Study 1: Muscle forces measured using the computational and experimental models correlated well (ICC ≥ 0.7; Figure 2), particularly in the vertical and varus positions (ICC > 0.9), where forces usually deviated less than 5 N. Correlation was weakest in the valgus position (ICC ≥ 0.7) but still significant (p ≤ 0.001).

Study 2: Changing the radial head height did not influence the forces recorded at different radial head heights (Table 1). The muscles forces at different radial head heights all correlated excellently (ICC > 0.94) to each other in both the computational and experimental model. Also, the max difference was found to be < 3 N for biceps and brachialis in the experimental model and < 6N for biceps and brachialis in the computational model.

Discussion: The results of study 1 demonstrate that a computational model can accurately replicate the forces needed to flex a phantom limb in 3 different positions. The computational model correlated well in all positions (ICC ≥ 0.7) to the experimental results, successfully validating the computational model. The valgus position showed the weakest correlation of the three positions. Since, in the valgus position, both the biceps and brachialis contribute to elbow flexion, their relative contributions can vary while providing the same net flexion moment. The differences in biceps and brachialis forces are likely related to differences in how the two methods balance muscles, and merits further investigation. Study 2 found that the muscle forces correlated excellently (ICC > 0.94) at three different radial head heights demonstrating that radial head height does not influence the muscle forces. The maximum difference between the muscles loads was larger in the computational model than the
experimental model. The difference occurred at flexion angles <15 degrees suggesting that the initial boundary conditions could be slightly different, meriting further exploration into these conditions. Combined, these studies show that a computational model can be used to predict the muscle forces generated during experiments with a physical simulator, and that clinical outcomes due to procedures such as radial head lengthening or shortening can be predicted computationally.

Significance: A validated computational model can drastically improve our understanding of elbow joint motion while reducing the time and cost burdens associated with in-vitro experiments. Our current study shows that a computational model can accurately replicate a physical phantom in three separate positions as well as replicate a clinical condition of radial head implant over or under-lengthening.

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Figure 1. In-vitro testing apparatus with phantom elbow in the valgus position. Cable guides were used to maintain physiological lines of action for the biceps (green), brachialis (red) and triceps (blue).
Figure 2. Computational (virtual) and experimental (phantom elbow) muscle forces during flexion for biceps, brachialis and triceps, in the (A) vertical, (B) varus and (C) valgus loaded positions. The experimental and computational forces correlated well in all positions.

<table>
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<th>Muscle</th>
<th>ICC</th>
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<th>Max Std. Error (N)</th>
<th>Max Difference (N)</th>
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</table>

Table 1. Statistical analysis comparing muscle forces at three different radial head heights. The muscle loads correlated excellently in both the computational and experimental model demonstrating that the height of the radial head did not affect the muscle forces during flexion.

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