

**CAN A SIMULATION-ASSISTED FORMULATION OF CO-CONTRACTION INDEX  
LEAD TO PREDICTION OF JOINT STIFFNESS?**

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**INTRODUCTION**

Co-activation of agonist and antagonist muscles is an important tool used by motor control system to modulate joint stiffness and thus joint stability [1]. Abnormal muscle co-activation patterns were commonly found in hemiparetic stroke patients during gait [2], which could cause joints to be either instable or too stiff during gait. To quantify muscle co-activation, Clinicians have developed different variants of co-contraction index (CCI) [3,4], but the reliability of these CCI formulations in describing muscle co-contraction are subjected to limitations such as: 1. the formulations use unnormalized muscle excitation, e.g. muscle electromyography (EMG) amplitude, which does not translate directly into muscle’s true activation. 2. these formulations are based on the activation comparison between only one agonist and one antagonist muscle, the activation of a muscle affected by neuromuscular disorder could misrepresent the activation of entire muscle group and hence distort CCI, the arbitrariness in muscle selections further adds unreliability; 3. these formulations take sums of the muscle activation over various phases of gait, information on the peak muscle co-contraction, often critical in clinical evaluation, is lost in this representation.

Clinicians rely on CCI to express muscle co-activation for the sake of simplicity, but the ideal method to quantify muscle co-activation and subsequently joint stiffness is to estimate force exerted by muscles about the a joint [5]. One limitation of existing CCI formulations prevents them from accurately quantifying joint stiffness is that the formulations measure only the relative comparison of activation between agonist and antagonist muscles and convey no information on the absolute magnitude. One extreme case to illustrate this limitation is when activation of both agonist and antagonist muscles are equally small, the CCI would be 100%, but the joint stiffness would be minimum.

This study seeks to explore the feasibility of using a minimally modified CCI formulation to

address the aforementioned limitations so that it can lead to prediction of joint stiffness. Since CCI is a metric commonly used by clinicians, the modified formulation should use mainly clinical quantities that can be readily measured.

**METHODS**

In a separate study, an EMG-driven model framework was built to calibrate model and estimate muscle force from the data of a stroke patient [6]. Results of this study were substituted into a joint stiffness formulation [7].

This study started first with a commonly used CCI formulation [3], but replaced muscle EMG with muscle activation. Instead of comparing the output of one antagonist (ANT) muscle against that of one agonist (AGO) muscle, e.g. activation of tibialis anterior and soleus. We calculated CCI by comparing the activation sum of ANT and AGO muscle groups, e.g. dorsi-flexors and plantar-flexors. In addition, CCI was computed at each percent of gait cycle rather than being computed over phases of the gait cycle. The role of each muscle group was defined dynamically, e.g. a dorsi-flexor would be the AGO muscle group had the ankle undergone dorsiflexion from current point to next in gait cycle. These modifications were reflected in eq1.

$$CCI_0 = \frac{2 \sum a_{ANT}}{\sum a_{ANT} + \sum a_{AGO}} \quad (eq1)$$

CCI<sub>0</sub> computed using eq1 did not show strong linear relationship with joint stiffness. To bridge the gap between CCI and joint stiffness, a muscle-specific coefficient, *b* was assigned to adjust the muscle activation. A quadratic polynomial of joint angle and velocity, *f*( $\theta, \dot{\theta}$ ) was used as multiplier on the activation ratio between ANT muscles and all muscles. The modified formulation CCI\* is shown in eq2.

$$CCI^* = \frac{2 \sum_{i=1}^{n_{ANT}} a_{ANT_i} b_i}{\sum_{i=1}^{n_{ANT}} a_{ANT_i} b_i + \sum_{i=1}^{n_{AGO}} a_{ANT_j} b_j} f(\theta, \dot{\theta}) \quad (eq2)$$

where  $f(\theta, \dot{\theta}) = (a_1\theta + a_2\theta^2 + a_3\dot{\theta} + a_4\dot{\theta}^2)$

The data of 10 walking trials at a fixed speed for a stroke patient were used for this study. 7 trials were selected to form the training set and the other 3 trials formed the test set. An optimization process was performed to maximize correlation between CCI\* and joint stiffness by adjusting parameters  $a_1 \sim a_4$  and  $b_i$  and using training set data. The formulation was then evaluated with test set data.

## RESULTS AND DISCUSSION

Correlation between CCI<sub>0</sub> and joint stiffness was not strong using existing CCI formulation (eq1). However, using CCI\* formulation (eq2), the correlation between CCI\* and joint stiffness improved significantly as shown in Table 1.

**Table 1.** Pearson correlation coefficient between CCI\* and joint stiffness at each joint for trials selected as training set and testing set, expressed in avg (std)

	Training	Test
	N_trials = 7	N_trials = 3
Hip FE	0.96 (0.02)	0.93 (0.05)
Hip AA	0.96 (0.02)	0.95 (0.04)
Hip Rot	0.80 (0.07)	0.84 (0.02)
Knee FE	0.66 (0.08)	0.56 (0.16)
Ankle FE	0.95 (0.02)	0.97 (0.00)
Subtalar IE	0.82 (0.15)	0.90 (0.06)

For the training set, strong linear relationship ( $r > 0.80$ ) was observed between CCI\* and joint stiffness for all joints except knee joint, but the correlation at knee joint ( $r = 0.66$ ) still indicated a moderate linear relationship between CCI\* and joint stiffness. For the test set, strong linear relationship ( $r > 0.80$ ) was again observed between CCI\* and joint stiffness for all joints except knee.

By applying the CCI\* formulation derived from data in the training set to data in the test set, the

formulation yielded comparable level of correlation, except at knee joint ( $r = 0.66$  vs  $r = 0.56$ ). The drop was mainly due to the low  $r$  value in one trial (test trail #1, see Figure 1). Overall, the CCI\* formulation showed consistency in matching the magnitude profile of joint stiffness, evident in the transition from training set to test set.

## CONCLUSIONS

This preliminary study substantiated the feasibility of matching CCI from a slightly modified formulation to joint stiffness. It could be potentially beneficial to the clinicians in joint stability quantification. Future work should focus on helping clinicians determine the values of the added parameters in the new formulation using clinical quantities can be readily measured.

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