The current muscle model recommended for general use within the OpenSim v3.0+ software system is the “Millard2012EquilibriumMuscle” tool (Millard et al., 2013). However to improve numerical stability and computational efficiency the default settings of the “Millard2012EquilibriumMuscle” tool in OpenSim yield small active forces at fiber lengths where no active force can be generated. Specifically, normalized fiber lengths of less than 0.5 or greater than 1.5 on the normalized force-length curve produce forces of 10% of maximum isometric force. Physiologically, those normalized lengths should not produce any active force. In addition, the default minimum muscle activation is defined as 0.01 (1% of full activation). Therefore, with the default parameters specified in the “Millard2012EquilibriumMuscle” tool, the model does not simulate 0% muscle activation and the resulting force output includes a force that does not arise from the passive muscle force-length curve.

The purpose of the short communication, that this appendix complements, is to both incorporate the length-dependent passive forces of the extrinsic index finger muscles into a biomechanical model of the upper limb and to demonstrate their influence on combined passive movements of the wrist and hand. In order to generate simulations involving 0% muscle activation and muscle force outputs that only arise from the passive muscle force-length curve we edited the default parameters set in the “Millard2012EquilibriumMuscle” tool in OpenSim v3.2. The parameters were edited to replicate the force generating curves that have been implemented in previous kinematic and dynamic models (Holzbaur et al., 2005; Saul et al., 2015). The previously developed Holzbaur 2005 and Saul 2015 dynamic upper extremity models have been used extensively within and outside of our lab with at least 320 citations between the two models (Web of Science, 2017).

Our edited version of the “Millard2012Equilibrium” muscle model was benchmarked relative to “Muscle Model 4”, implemented in the SIMM and Dynamics Pipeline frameworks. Within the Dynamics Pipeline platform, “Muscle Model 4” is an algorithm based on the well-known muscle modeling work described in Lisa Schutte’s PhD dissertation (Schutte, 1992).

In order to avoid complications associated with computational challenges that arise when simulating the dynamics of the small masses and inertias of the hand, we evaluated the performance of our edited version of the “Millard2012EquilibriumMuscle” tool in OpenSim by performing the simulations with a musculoskeletal model of the upper extremity isolated to the elbow joint. Identical, simplified musculoskeletal elbow models were implemented within both the SIMM and OpenSim platforms. The models included only 4 muscles; the Triceps Long head, Triceps Lateral head, Biceps Long head, and Biceps Short head. The muscle paths, muscle-tendon geometry, and force generating properties were replicated in both models as described previously (Saul et al., 2015).

A gravity-driven, forward dynamic simulation was performed in each platform to compare the passive behavior of each muscle tool during the simulations. The elbow was initially set to 40 degrees of flexion and then allowed to fall with gravity towards an equilibrium posture. The simulation was run for five seconds. The passive muscle dynamics of the modified "Millard2012EquilibriumMuscle" tool within the OpenSim v3.2 platform were then compared to the passive muscle dynamics of the "Muscle Model 4" tool within the Dynamics Pipeline platform during the gravity driven simulations.

Within both models the long head of the bicep brachii's muscle-tendon unit remains lengthened beyond its slack length throughout the simulation. The muscle-tendon slack length is the length at which the muscle-tendon unit begins to produce passive forces (Figure 1, see also Eq 8 from manuscript). The short head of the biceps brachii oscillates about its muscle-tendon slack length. The muscle-tendon lengths of both heads of the triceps remain below the muscle-tendon slack length (Figure 1). When the muscle-tendon unit is shorter than the slack length the muscle does not produce passive muscle forces (Eq 8 from manuscript). Therefore only the heads of the biceps produce passive forces during this simulation.

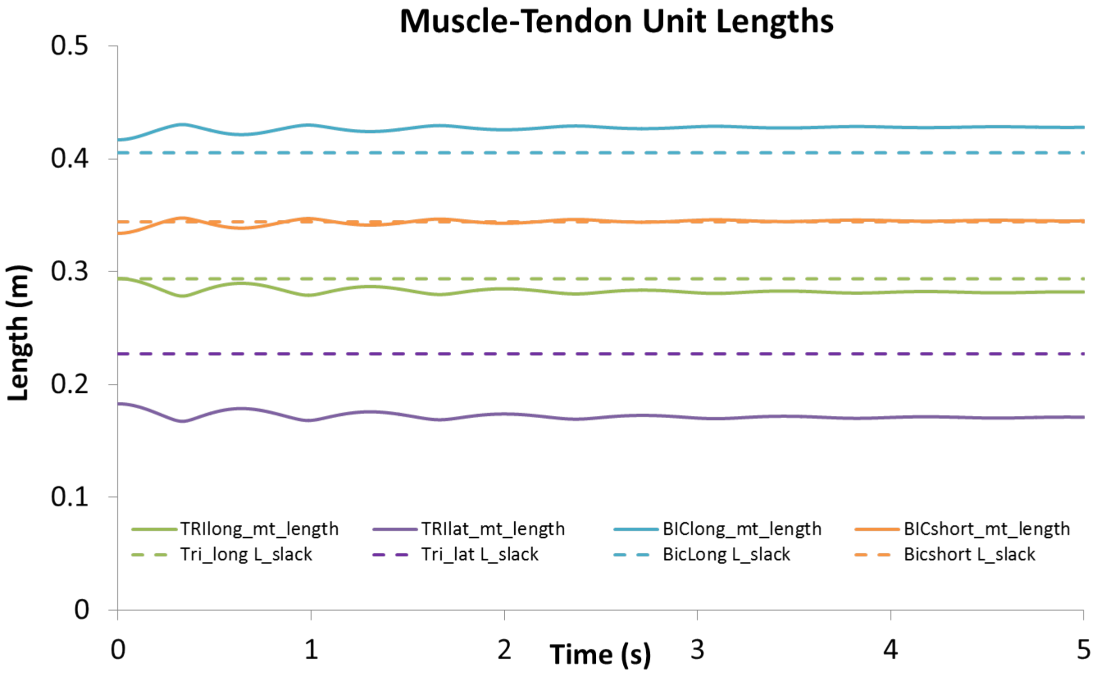

Figure 1: Muscle-tendon unit lengths (solid) over time of the triceps long head (green), triceps lateral head (purple), biceps long head (blue), and biceps short head (orange) during the passive forward simulation using the modified "Millard2012EquilbiumMuscle" tool in OpenSim v3.2. The slack length, the length at which passive forces begin, of each muscle is plotted in the dashed lines.

The passive dynamic performance of our edited version of the "Millard2012EquilbriumMuscle" tool implemented in OpenSim v3.2 behaves in the same manner as the "Muscle Model 4" implemented in the Dynamics Pipeline. Of interest is the dynamic performance of the muscles producing force, therefore we are only presenting the performance of the biceps and are not presenting the performance of the triceps. In particular, after a brief initialization, the distribution of muscle-tendon length changes between the muscle fiber and the tendon for the biceps is replicated in both tools (Figure 2). The length changes of the biceps long head occur primarily in the muscle fiber (Figure 2). The length changes of the biceps short muscle depends on whether the muscle-tendon length is longer or shorter than the slack length (Figure 2). When the muscle-tendon unit is longer than the slack length the change occurs in muscle fiber. When the unit is shorter than the slack length the change occurs in the tendon and the fiber length remains at the length in which passive forces begin (Figure 2).

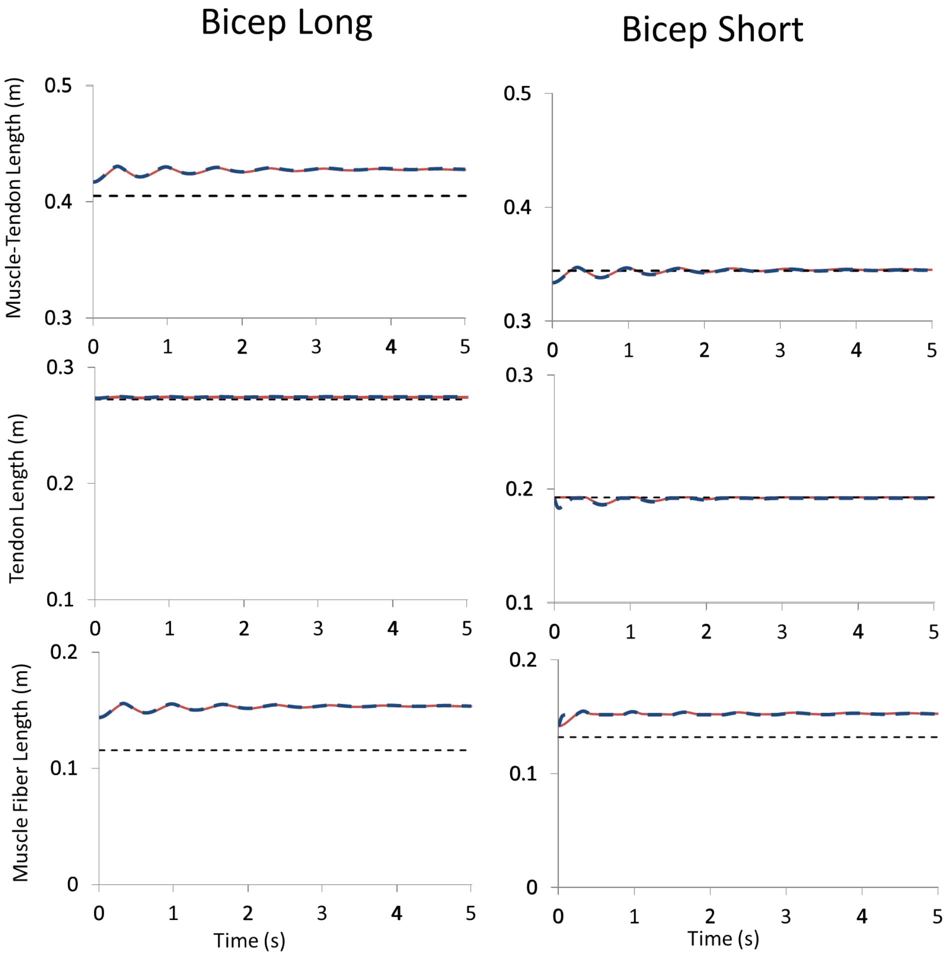

Figure 2: The muscle-tendon unit (top), tendon (middle) and muscle fiber (bottom) lengths of the biceps long head (left column) and short head (right column) of the Millard2012Equilibrium tool (blue dashed) and Muscle Model 4 tool (red solid). The slack lengths of the muscle-tendon units, tendons, and muscle fibers (black dashed) are displayed in each graph.

Given the assumption of no muscle activation or muscle active force for this analysis, the distinct muscle models in the two different software environments default to models of two passive elastic elements, connected in series, in which the tendon is at approximately 20 times stiffer than the muscle fibers. By definition, when the muscle-tendon unit is longer than its slack length the fiber and tendon are also lengthened beyond their slack lengths. Due to the relatively high tendon stiffness, passive length changes occur in the muscle fibers with relatively little concomitant change in tendon length. This expected behavior is observed in both biceps muscles during the simulations, in both platforms (Figure 2).

The resultant system dynamics of the musculoskeletal model show that the elbow angle over time using each muscle tool match well (R^2=0.989, RMSE=0.711 over the whole time period) (Figure 3). The simulations are nearly identical for the first 2.5 seconds (R^2=0.997, RMSE=0.506 for seconds 0 to 2.5). After 2.5 seconds the joint posture between the models deviate (R^2=0.794, RMSE=0.870 for seconds 2.5 to 5). These differences likely occur due to numerical differences during the calculation of muscle force between the two tools and platforms. As the simulations continue these differences propagate and lead to the increasingly different joint angles.

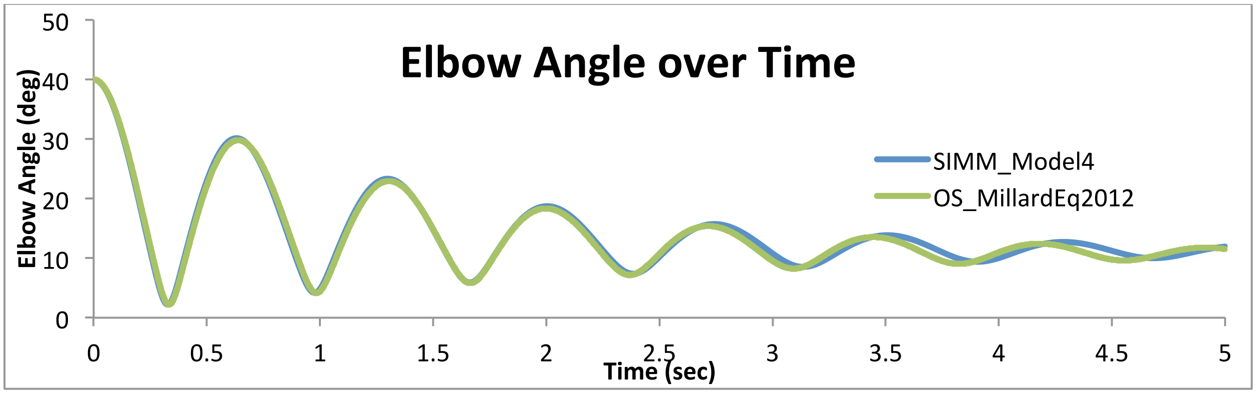

Figure 3: Plot of elbow angle over time for a gravity driven simulation within the SIMM and Dynamics Pipline platform using Muscle Model 4 (blue) and the OpenSim platform Millard2012Equilbirum tool (green).

We conclude that the parameter changes we implemented to enable simulations of purely passive muscle forces produce acceptable results, consistent with two elastic elements of varied stiffness connected in series, and replicated when the same parameters are implemented in a different muscle model in a different software platform. Minimal differences in the outputs of the muscle model are observed over a 5 second simulation, as evidenced in Figures 2 and 3. The main caveats to our implementation are associated with computational robustness: using the default parameters of the "Millard2012EquilbirumMuscle" tool yields faster computation times, and increases computational stability. Our modifications increase the computation time of the simulations and introduce the potential that the muscle tool may become unstable and crash during dynamic simulations; however we did not experience any crashes during the dynamic simulations at the hand or elbow. These trade-offs were necessary for the purposes of this paper.