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Original Research Article

Comparison of OpenSim and AnyBody modeling system™ predictions in biomechanical modeling of upper extremities

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ABSTRACT

Background: The study of muscle forces in upper extremities is pivotal for advancements in biomechanical modeling, contributing significantly to the field of orthopedics, rehabilitation, and sports science. Despite the prominence of OpenSim and AnyBody modeling system™ in this domain, a gap persists in comparative analyses specifically targeting muscle force predictions in upper extremity motions.
Methods: This study compares the predictions of muscle forces in static elbow flexion, shoulder flexion, and shoulder abduction using OpenSim and AnyBody modeling system™, hypothesizing significant differences in predictions attributable to their distinct modeling methodologies and assumptions. This work utilized generic models without subject-specific data and conducted simulations in both software environments, focusing on the magnitude and activation of major muscle forces under predefined kinematics.
Results: OpenSim and AnyBody modeling system™ produced similar results when simulating elbow flexion, with both software predicting forces in the major muscles required to maintain the posture. However, discrepancies were observed between the two software for muscle force predictions during the shoulder flexion and abduction movements. AnyBody modeling system™ appeared to be more robust as it included all the upper extremity muscles and predicted the major muscles forces required for these movements more accurately compared to OpenSim.
Conclusions: The results of this study show significant differences in muscle force predictions between OpenSim and AnyBody modeling system™, attributed to the unique modeling approaches, especially in representing muscle-tendon complexes and joint dynamics.

Keywords: Muscle force prediction, Upper extremity motions, OpenSim, AnyBody modelling system™

INTRODUCTION

The study of the human musculoskeletal system using modeling and simulation has become an integral part of biomechanical research as it enables the study of cause-and-effect of the muscles which are difficult to measure *in vivo*. The musculoskeletal models used in simulating human motion are based on engineering concepts, physiological principles, and 3D imaging technology.[1] These computational measurements not only assist in understanding the muscle function but also helps in understanding joint reaction forces, study pre-and-post surgical and rehabilitation interventions, facilitate personalized treatment strategies, and optimize athletic performance.[2-4]

Human and animal musculoskeletal systems are mechanically very complex, thus computational models are simplified to function reasonably well and streamline their application in research and clinical practices. Typically, these models are based on either finite element analysis (FEA) or three-dimensional rigid body dynamics which considers bones as rigid bodies connected by various joints, each with different degrees of freedom

(DOF).[5] Simulating the intricate structure of muscles and their recruitment patterns involves certain assumptions, often represented through objective functions.

Given the differences in the anthropometry and muscle force generating capacity between individuals, it is challenging to create a single universal musculoskeletal model that can be used for studying subject-specific motion.[6] Instead, generic human musculoskeletal models have been developed based on the anatomical and physiological information obtained from detailed cadaver studies.[7-9] Later, these models are scaled to match an individual's anthropometry for accurate musculoskeletal analysis within multiple areas such as ergonomics, orthopedics, and occupational health.[6,10,11]

In orthopedic and rehabilitation research, OpenSim and AnyBody modeling system™ stand out as the two prominent software for the analysis of human movement and muscle functions. OpenSim is an open-source software system providing a platform for creating and analyzing the dynamic simulation of movements to provide an insight into neuromuscular coordination, gait cycle, internal loading, athletic performance and the biomechanical effects of different treatments.[12,13] On the other hand, AnyBody modeling system™ is a commercial software for creating detailed models of the human musculoskeletal system as well as their interactions with environment.[14,15]

OpenSim and AnyBody modeling system™ have been widely used to study the lower limb motions using both generic and subject specific musculoskeletal models for kinematics and dynamics analysis.[16-21] Researchers utilized markers and ground reaction forces to predict the muscle and joint forces using the musculoskeletal models available in OpenSim and AnyBody modeling system™, then compared the predicted muscle forces with the muscle activations obtained experimentally using electromyography (EMG). There are few studies that compared muscle force predictions from OpenSim and AnyBody modeling system™, particularly for lower limb motions. Trinler et al conducted a study to compare joint kinematics, joint kinetics, and estimated muscle forces between OpenSim and AnyBody modeling system™ for lower extremity motions and identified differences in hip angles, sagittal ankle motions, knee movements and muscle forces including those in the triceps surae and the biceps femoris short head.[22] Kim et al conducted another study and reported that when matched and generic models were used in both software, the subject-specific model reported high consistency in muscle activation levels compared to generic models.[21] For different walking speeds, Alexander et al reported that AnyBody modeling system™ and OpenSim exhibited consistent trends in responses with differences in the extent of errors and variability in muscle force predictions.[23] These findings underscore the importance of understanding each software and model's specific characteristics and assumptions to apply to clinical and research settings more accurately.

Few complex upper extremities models have been developed to study the upper limb motion such as delft shoulder and elbow model (DSEM), upper extremity kinematic model, upper extremity dynamics model (UEDM), thoracoscapular shoulder model, and AnyBody shoulder arm model across two platforms. However there remains a lack of specific research comparing the muscle force predictions of OpenSim and AnyBody modeling system™ for upper extremity motions.[14,25-30]

Given the absence of direct comparisons of OpenSim and AnyBody modeling system™'s muscle forces predictions in the upper extremities, this study aims to compare the predictions of muscle forces using these two different modeling environments during upper extremity motions. This work will primarily focus on simulating three common postures specifically static elbow flexion, shoulder flexion, and shoulder abduction using UEDM from OpenSim and AnyBody modeling system™ shoulder arm model. It is hypothesized that there are significant differences in muscle force predictions for the upper extremities between OpenSim and AnyBody modeling system™ modeling software when simulating static elbow flexion, shoulder flexion, and shoulder abduction. These differences will be evident in the magnitudes and distributions of the muscle forces, due to the distinct modeling methodologies and assumptions built into each software, particularly in how they represent muscle-tendon complexes, joint kinematics, and dynamics. Identifying these differences both quantitatively and qualitatively aims to clarify the strengths and limitations of each platform, contributing to a deeper understanding of their value in biomechanical modeling.

METHODS

This study was conducted from May 2023 to February 2024, at the biomechanics laboratory of the department of mechanical, industrial, and manufacturing engineering and the department of bioengineering at the University of Toledo, Toledo, Ohio, United States of America.

Models' description

The generic models from OpenSim and AnyBody modeling system™ were implemented using predefined kinematics and joint angles. These generic models represent the anthropometry and force generating capacity of the 50th percentile adult male. UEDM available on OpenSim via simtk.org and shoulder arm model from AnyBody modeling system™ were selected and used for this study.[31]

The UEDM is composed of seven segments: thorax, clavicle, scapula, humerus, ulna, radius, and hand as shown in Figure 1. These segments form seven articulation surfaces corresponding to seven DOF and allow for shoulder rotation (internal/external), elevation plane (plane along which the humerus moves), shoulder elevation (angle between anatomical position and elevated arm which can be abduction/adduction or flexion/extension based on elevation plane), elbow flexion, forearm rotation, wrist flexion and wrist deviation. Further, the scapula and clavicle motions are defined by the linear regression equation based on the shoulder elevation as defined by de Groot and Brand.[32] The UEDM comprises of fifty Hill-type muscle-tendon actuators, representing the thirty-two muscles and muscle compartments that span the shoulder, elbow, forearm, and wrist with single line of action. These muscles were implemented by Millard et al in their model where muscles were defined by insertion and origin point within the geometry, optimal fiber length, maximum isometric force, tendon slack length, pennation angle, active force length curve and force velocity curves as defined by Thelen and Millard.[33,34]

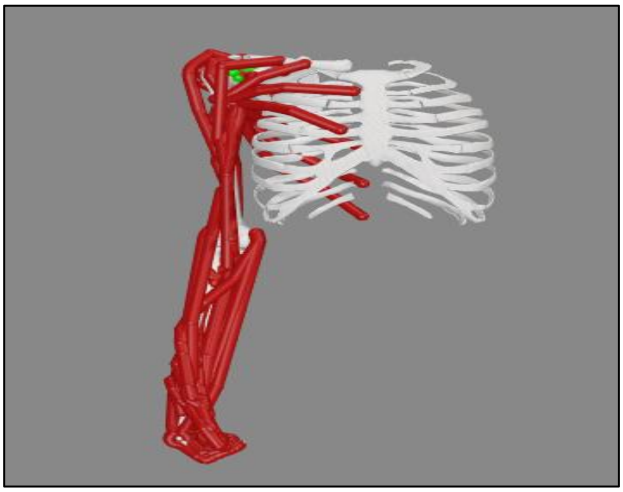

Figure 1: Pictorial representation of anterior view of upper extremity model available in OpenSim in anatomical position.[28]

In AnyBody modeling system^{TM}, this study started with the “free posture full body shoulder rhythm” model available under the subsection of free posture models on the AnyBody managed model repository (AMMR) v2.0.0 of AMS v.7.1.0.5957.[35] The full body model was then configured to shoulder arm model defining the ARM_RIGHT in ON state and turning OFF other components like ARM_LEFT, LEG_MODEL, and corresponding muscles as depicted in Figure 2. This model is based on the data from Veeger et al and Van der Helm et al study that defines mass and moments of inertia based on anthropometric measurements from a cadaveric study as well as muscle parameters.[36,37] The body parts are defined using the relation between body mass and height of the subjects corresponding to the 50th percentile of European male as defined by Winter.[38] The model contains ten DOF at sternoclavicular joint, glenohumeral joint, elbow joint and wrist joint which can be controlled from the mannequin.any file. Like OpenSim, it also describes the scapula and clavicle motions in terms of the glenohumeral joint angles, also known as shoulder rhythms. There are 118 muscle-tendons units in the AnyBody modeling system^{TM} with at least two lines of action defining points of origin and insertion. The muscles were defined using AnyMuscleModel3E which is a full-blown Hill model that contains contractile element, serial-elastic and parallel-elastic element representing active properties of the muscle fibers, elasticity of the tendon and passive stiffness of the muscle fibers, respectively. The muscle parameters such as strength of muscles, neutral fiber length, elasticity factors of the tendon, pennation angle are implemented from multiple sources which can be found in detail in AnyBody documentation and muscle.any file under the body model.[14,39]

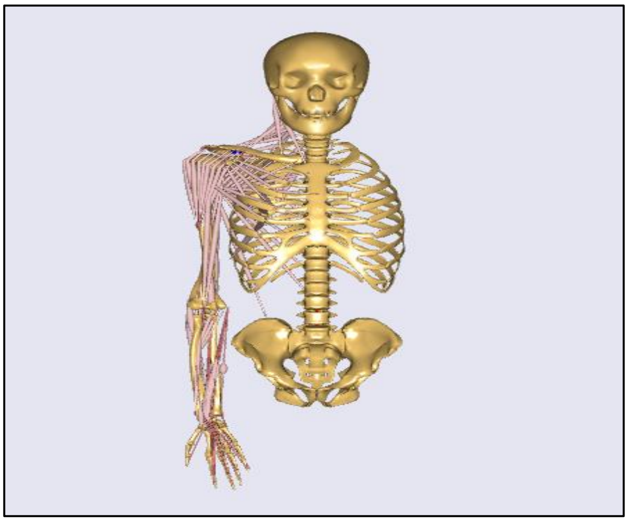

Figure 2: Pictorial representation of anterior view of shoulder arm model available in AnyBody modeling system^{TM} in anatomical position.[14]

Kinematics definition

This work simulates the kinematics of three static test cases namely 90-degree elbow flexion, 80-degree shoulder flexion and 90-degree shoulder abduction in OpenSim and AnyBody modeling system^{TM}.

In OpenSim, elbow flexion of 90-degree is defined by changing the generalized coordinate elbow-flexion from 0 to 90 degree within the graphical user interface (GUI) as illustrated in Figure 3 A. For shoulder flexion two sets of coordinates namely elv_angle and shoulder_elv, were used. The elv_angle is changed from the default angle of 0° to 90°. Here, 0° places the plane of elevation in the frontal plane where abduction-adduction motion occurs, and 90 degrees corresponds to the sagittal plane where flexion-extension motion takes place. To achieve the 80 degree of shoulder flexion shoulder_elv angle is changed to 80° as shown in Figure 3 B. For shoulder abduction a similar procedure is followed where elv_angle is set to 0 degree and shoulder_elv to 90 degrees within the OpenSim GUI as shown in Figure 3 C. Finally, and with all coordinates locked, a short forward simulation was run to obtain the motion file (.mot file) for all three postures to be used as input file for inverse dynamics.

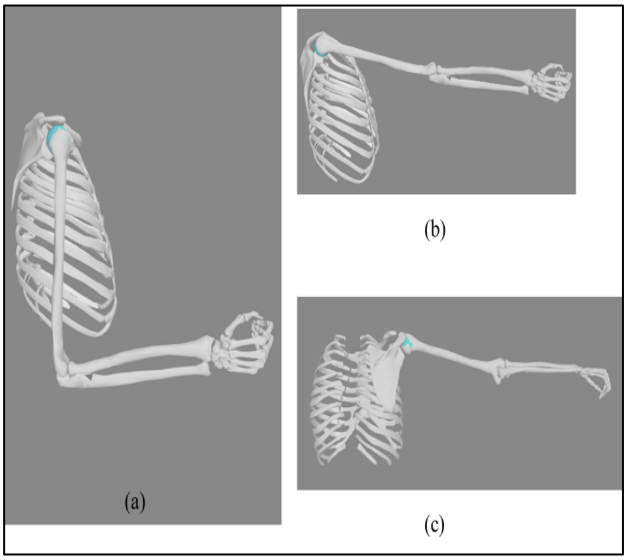

Figure 3 (a-c): Simulated motions in OpenSim elbow flexion of 90 degrees in sagittal view, shoulder flexion of 80 degrees in sagittal view and shoulder abduction of 90 degrees in posterior view.

In AnyBody modeling system™, for elbow flexion, AnyVar elbow flexion was defined as 90 degrees to obtain the final posture as shown in Figure 4 A. Shoulder flexion was obtained by changing the input value of AnyVar glenohumeral flexion to 80 degrees as shown in Figure 4 B. Similarly, shoulder abduction was performed by changing AnyVar glenohumeral abduction to 90 degrees as shown in Figure 4 C. All these changes were made within the mannequin.any file of AnyBody Modeling System™ and all angular velocities were set to zero for all rotating angles to simulate static cases.

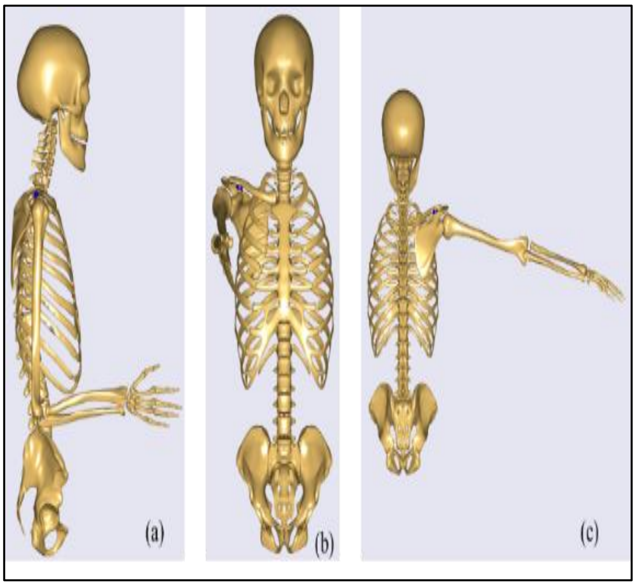

Figure 4 (a-c): Simulated motions in AnyBody elbow flexion of 90 degrees in sagittal view, shoulder flexion of 80 degrees in front view and shoulder abduction of 90 degrees in posterior view.

Muscle force predictions

Muscle forces were predicted using OpenSim v4.4 and AnyBody v7.1 during the specified upper extremity motions.[12-14] Since this work only simulates the static posture and no markers' data were used from a subject, calibration of the model was not required to match the experimental data. Instead, the generic models in their standard settings were used and no changes in the DOF of the joints, mass and inertial properties were made. Additionally, since the number of muscles is greater than the available DOF an inverse-dynamics based optimization problem is solved to predict the muscle forces.[12-14]

In OpenSim, muscle forces prediction is done in two steps. First, the motion file (.mot file) is used as an input to run an inverse dynamic to obtain the joint moments. Then either static optimization (SO) or computed muscle control (CMC) algorithms is used to solve the muscle redundancy problem. Alternatively, within the SO inverse dynamics and optimization are simultaneously solved to predict muscle forces. Since it was just a simple static simulation, this work utilizes SO to predict muscle forces associated with the given static posture. Along with the motion file, reserve actuators were appended to each degree of freedom to provide any additional force required to obtain the desired kinematics and to successfully run the simulation. In OpenSim, muscle redundancy problem was solved minimizing the sum of muscle activations as follows:

$$J = \sum_{m=1}^{n} (a_m)^3 \quad (1)$$

Where n is the number of muscles and $\boldsymbol{a_m}$ is the activation level of muscle m at a discrete time step. The simulation was completed when it ran for a specified time period of 1 second without any error message. Further, the reserved actuators force predictions were checked to make sure that they have no forces greater than 10 N.[40] this same procedure was followed for all the three test cases of elbow flexion, shoulder flexion and shoulder abduction followed by data visualization using excel.

In AnyBody modeling system™, prior to running an inverse dynamics analysis, a calibration study was performed using the initial calibration study option within the software for advanced muscle model (MuscleModel3E) that was used in this study. This ensures that the muscles will have optimum contractions and fiber length including tendon and ligaments length adjustments for the defined kinematics. An inverse dynamics analysis was then run to solve the muscle redundancy problem using following polynomial muscle recruitment criterion:

$$G = \sum_{i=1}^{n(M)} \left(\frac{f_i^{(M)}}{N_i} \right)^3 \quad (2)$$

Where G is an objective function, $n^{(M)}$ is the number of muscles, $f_i^{(M)}$ is the respective predicted muscle force in newtons, and N_i is isometric muscle strength in Newtons. HDF5 is a typical output file from AnyBody modeling system^{TM}. HDF5 output files were converted to excel CSV file using a Python script for data visualization.

Predicted muscle forces from OpenSim and AnyBody modeling system^{TM} were then compared with each other and evaluated with existing EMG data to evaluate the accuracy of the results and to determine which of the two software is more viable for future research on the upper extremities.

RESULTS

Muscle forces prediction during static elbow flexion, shoulder flexion, and shoulder abduction were obtained using AnyBody modeling system^{TM} and OpenSim musculoskeletal models. The following results were obtained.

Elbow flexion

The results for muscle predictions using both software during elbow flexion is shown in Figure 5. Both models identified the brachialis as the primary muscle contributor at this position, with AnyBody Modeling System^{TM} and OpenSim predicting this muscle force as 51 N and 44 N, respectively, highlighting its pivotal role in this movement. Additionally, OpenSim predicted somehow greater forces in the biceps of 26 N compared to AnyBody modeling system^{TM}'s prediction of 20 N. Brachioradialis forces were closely matched between AnyBody Modeling System^{TM} (11 N) and OpenSim (9 N). Notably, OpenSim exclusively predicted muscle forces in the triceps of 13 N during elbow flexion, while AnyBody modeling system^{TM} did not predict any forces in this muscle.

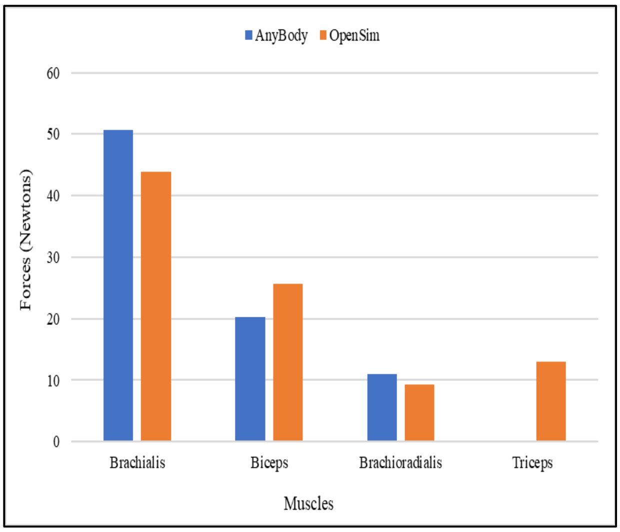

Figure 5: Prediction of major muscle forces during elbow flexion using OpenSim and AnyBody modeling system^{TM}.

Shoulder flexion

The results for muscle predictions using both software during shoulder flexion is shown in Figure 6. During shoulder flexion, both software predicted the highest muscle forces in the deltoid, with OpenSim and Anybody modeling system^{TM} predicting this muscle force as 545N and 490N, respectively, emphasizing its significance in this movement. In contrast, the AnyBody modeling system^{TM} predicted muscle forces in the serratus, trapezius and long head of the biceps of 88N, 128N and 50N, respectively. Forces in these muscles were not predicted by OpenSim. On the other hand, a significant force in the triceps was only predicted by OpenSim (422 N). Both software predicted zero force in the coracobrachialis. The predicted force in infraspinatus muscle was greater by more than two times in OpenSim (215 N) compared to AnyBody modeling system^{TM}'s prediction (95 N).

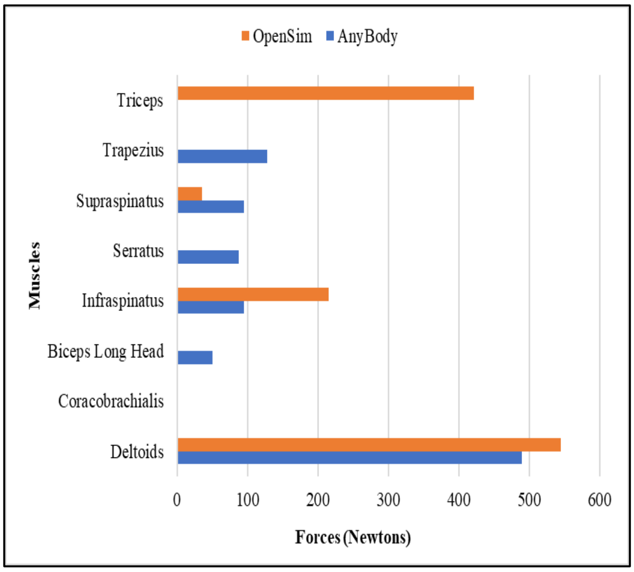

Figure 6: Prediction of major muscle forces during shoulder flexion using OpenSim and AnyBody modeling system^{TM}.

Shoulder abduction

The results for muscle predictions using both software during shoulder abduction is shown in Figure 7. During shoulder abduction, both software predicted the highest muscle forces in the deltoid, with OpenSim and Anybody modeling system^{TM} predicting this muscle force as 746 N and 508 N, respectively, AnyBody modeling system^{TM} predicted a substantial force in the subscapularis of 510 N while the force in this muscle was predicted as 142 N in OpenSim. The forces in the trapezius, serratus, supraspinatus and infraspinatus muscles were only predicted in AnyBody modeling system^{TM} as 125 N, 82 N, 85 N, and 132 N, respectively. The most notable difference was observed when predicting the force in the triceps muscle, with OpenSim predicting a force of 571 N while AnyBody modeling system^{TM} predicting a force of 24N.

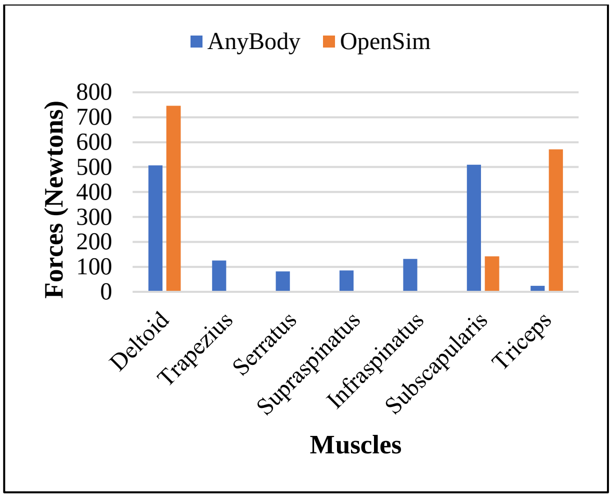

Figure 7: Prediction of major muscle forces during shoulder abduction using OpenSim and AnyBody modeling system™.

DISCUSSION

In this study muscle forces were predicted using AnyBody modeling system™ and OpenSim during elbow flexion, shoulder flexion and shoulder abduction. The results obtained from this study show differences between the muscle force predictions using both software highlighting the importance of a careful selection of the software environment and the corresponding musculoskeletal model. Even though the magnitude of the muscle force predictions were different between the two software, there were similarities in muscle activation patterns that was noteworthy.

The major elbow flexor muscles are the biceps brachii, the brachioradialis, and the brachialis.[41] Both software predicted muscle forces for these muscles confirming their role in elbow flexion. The magnitudes of the forces in these muscles were also relatively close, indicating that both software can precisely predict the primary muscles required to complete an action related to elbow joints alone. Interestingly, OpenSim did predict a contractile force for the triceps during elbow flexion, while AnyBody modeling system™ did not. This may indicate that the triceps engages to provide stability and balance to the elbow joint allowing better control while the agonist muscles provide the contractile forces necessary to simulate the range of motion.

Discrepancies were noted in the predictions of the muscle forces during shoulder flexion between the two software as shown in Figure 6. Results from an EMG analysis indicated that the deltoid, pectoralis major, supraspinatus, infraspinatus, serratus anterior, and trapezius were significantly activated during shoulder flexion.[42] While another article identifies anterior deltoid, coracobrachialis, and pectoralis major as major flexor and biceps brachii as a weaker agonist to the shoulder flexion.[43] The isometric contractions of these muscles allow for static shoulder flexion as well as stabilizing the humeral head within the glenoid.[44] In our simulation, AnyBody modeling system™, and in agreement with the literature, predicted muscle activations in the deltoid, supraspinatus, infraspinatus, serratus anterior, and trapezius during shoulder flexion. It is noted that OpenSim does not include the trapezius and serratus muscles in their model. Furthermore, OpenSim predicts large muscle forces for the triceps during shoulder flexion which contradicts the data available in the literature.[42]

During shoulder abduction, AnyBody modeling system™ predicted muscle forces in the deltoid, trapezius, serratus, supraspinatus, infraspinatus, and subscapularis which agrees with the literature.[45,46] On the other hand, OpenSim predictions lack muscle activations for the trapezius, serratus, supraspinatus, and infraspinatus. Furthermore, OpenSim predicts larger muscle forces in the triceps during shoulder abduction which does not agree with the literatures.[45,46] Because the trapezius and serratus muscles are not included in OpenSim, we believe that this software may depend on other muscles to achieve shoulder abduction resulting in them having higher forces.

The above differences between software predictions might be due to the different anthropometric data of 50th percentile US adult men in OpenSim and 50th percentile European adult men in AnyBody modeling system™. Based on anthropometry there might be certain variations on a segment mass and inertia which could result in different joint moments and subsequently muscle forces. The muscle definitions could be another reason for the differences in software predictions. Muscle properties in OpenSim were clearly identified using the available resources.[28,33] On the other hand, there was a lack of resources that explain the muscle's model properties in AnyBody modeling system™. This hindered the comparison of muscle properties between the software to identify the potential differences in their predictions. Further, AnyBody modeling system™ requires a calibration to be performed before conducting a simulation while using a Hill-type muscle model. On the other hand, OpenSim does not require any calibration. This calibration might help adjust muscle tendon length thereby reducing any excessive passive muscle forces. In addition, the upper extremity dynamic model (UEDM) of OpenSim does not include muscles like levator scapulae, rhomboid, serratus, sternocleidomastoid, and trapezius muscles of the upper extremities. This might raise a concern when using this software in simulating shoulder motions as the model predictions might not accurately portray the clinical scenarios.

It is important to note that both software couple humeral elevation to scapular rotation which does not accurately predict the muscle forces required to move the scapula and the subsequent upper extremity motions.[47] This produces excessive muscle forces in the rotator-cuff and deltoid muscles without including other muscles that help stabilize the scapula and may aid in stabilizing the glenoid during shoulder motions. The same reason can be used to explain the large force predicted in the triceps in OpenSim as this muscle crosses the glenohumeral joint. A more comprehensive model is thus required to be developed to simulate the independent motions of the scapula, humerus and subsequently the upper extremity motions to predict more realistically the forces in all muscles during these motions. Further, this study was conducted to simulate static positions with generic models. A dynamics analysis with scaled models could support the study outcome in the future.

CONCLUSION

In conclusion, both software, namely AnyBody modeling system™ and OpenSim, were in close agreement when predicting the primary movers of the elbow flexion, with slight variations in the force magnitudes which might be due to a difference in anatomical parameters. During shoulder flexion and shoulder abduction, AnyBody modeling system™ appears to be more accurately predicting muscle forces compared to OpenSim as it was in close agreement with the literature in terms of muscles activation patterns.[42,45,46] This is because OpenSim does not include several muscles in their model. Thus, AnyBody modeling system™ appears to be more viable in predicting muscle forces during the simulation of upper extremity motions.

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REFERENCES

1. Liu A, Wang P, Zhang JT, Jin Z, Zhang C. Application of musculoskeletal model in biomechanics research of knee joint. Int J Biomed Eng. 2014;37:56.
2. Buchanan TS, Lloyd DG, Manal K, Besier TF. Neuromusculoskeletal modeling: estimation of muscle forces and joint moments and movements from measurements of neural command. J Appl Biomech. 2004;20(4):367-95,
3. Smith SHL, Coppack RJ, Van den Bogert AJ, Bennett AN, Bull AMJ. Review of musculoskeletal modelling in a clinical setting: Current use in rehabilitation design, surgical decision making and healthcare interventions. Clin Biomechanics. 2021;83:105292.
4. Rasmussen J, Holmberg LJ, Sørensen K, Kwan M, Andersen MS, De Zee M. Performance optimization by musculoskeletal simulation. Movement Sport Sci. 2012;75:73-83.
5. Fisk JP, Wayne JS. Validation of a Computational Musculoskeletal Model of the Elbow in ASME 2007 Summer Bioengineering Conference. vol. ASME 2007 Summer Bioengineering Conference. 2007;647-8.
6. Akhundov R, Saxby DJ, Diamond LE, Edwards S, Clausen P, Dooley K, et al. Is subject-specific musculoskeletal modelling worth the extra effort or is generic modelling worth the shortcut?. PLoS One. 2022;17(1):e0262936.
7. Arnold EM, Ward SR, Lieber RL, Delp SL. A model of the lower limb for analysis of human movement. Ann Biomed Eng. 2010;38:269-79.
8. Delp SL, Loan JP, Hoy MG, Zajac FE, Topp EL, Rosen JM. An interactive graphics-based model of the lower extremity to study orthopaedic surgical procedures. IEEE Transactions on Biomed Eng. 1990;37(8):757-67.
9. Modenese L, Phillips AT, Bull AM. An open source lower limb model: Hip joint validation. J Biomech. 2011;44(12):2185-93.
10. Brito da Luz S, Modenese L, Sancisi N, Mills PM, Kennedy B, Beck BR, et al. Feasibility of using MRIs to create subject-specific parallel-mechanism joint models. J Biomechanics. 2017;53:45-55.
11. Lund ME, Andersen MS, De Zee M, Rasmussen J. Scaling of musculoskeletal models from static and dynamic trials. Int Biomech. 2015;2(1):1-11,
12. Delp SL, Anderson FC, Arnold AS, Loan P, Habib A, John CT, et al. OpenSim: open-source software to create and analyze dynamic simulations of movement. IEEE Trans Biomed Eng. 2007;54(11):1940-50,
13. Seth A, Hicks JL, Uchida TK, Habib A, Dembia CL, Dunne JJ, et al. OpenSim: Simulating musculoskeletal dynamics and neuromuscular control to study human and animal movement. PLoS Comput Biol. 2018;14(7):e1006223.
14. Damsgaard M, Rasmussen J, Christensen ST, Surma E, De Zee M. Analysis of musculoskeletal systems in the AnyBody Modeling System. Simulation Modelling Pract Theory. 2006;14(8):1100-11.
15. Who is AnyBody Technology?. Avaiable at: https://www.anybodytech.com. Accessed on 14 April, 2024.
16. Honert E, Powell B, Goehler CM. Estimating Individual Joint Contributions to Recorded Upper Extremity Movements Using OpenSim," in ASME 2013 Summer Bioengineering Conference. 2013:1B:V01BT59A001.
17. Ahmed S, Babski-Reeves K. Assessment of Upper Extremity Postures in Novice and Expert during Simulated Carpentry Tasks. Proceedings Human Factors Ergonomics Society Ann Meeting. 2012;56(1):1173-7.
18. Yu J, Zhang S, Wang A, Li W. Human gait analysis based on OpenSim in 2020 International Conference on Advanced Mechatronic Systems (ICAMechS). 2020;278-81.
19. Nandy A, Chakraborty P. A study on human gait dynamics: modeling and simulations on OpenSim platform. Multimedia Tools Applications. 2017;76(20):21365-400.
20. Lei Y, Yang F. Simulation Analysis and Study of Gait Stability Related to Motion Joints. BioMed Res Int. 2022;8417089.

21. Karimi MT, Hemmati F, Mardani MA, Sharifmoradi K, Hosseini SI, Fadayevatan R, et al. Determination of the correlation between muscle forces obtained from OpenSim and muscle activities obtained from electromyography in the elderly. Phys Eng Sci Med. 2021;44(1):243-51.
22. Trinler U, Schwameder H, Baker R, Alexander N. Muscle force estimation in clinical gait analysis using AnyBody and OpenSim. J Biomech. 2019;86:55-63.
23. Kim Y, Jung Y, Choi W, Lee K, Koo S. Similarities and differences between musculoskeletal simulations of OpenSim and AnyBody Modeling SystemTM modeling system. Journal of Mechanical Science and Technology. 2018;32(12):6037-44.
24. Alexander N, Schwameder H, Baker R, Trinler U. Effect of different walking speeds on joint and muscle force estimation using AnyBody and OpenSim. Gait Posture. 2021;90:197-203.
25. Nikooyan AA, Veeger HE, Chadwick EK, Praagman M, Helm FC. Development of a comprehensive musculoskeletal model of the shoulder and elbow. Med Biol Eng Comput. 2011;49(12):1425-35.
26. Van der Helm FC. Analysis of the kinematic and dynamic behavior of the shoulder mechanism. J Biomech. 1994;27(5):527-50.
27. Holzbaur R, Murray WM, Delp SL. A model of the upper extremity for simulating musculoskeletal surgery and analyzing neuromuscular control. Ann Biomed Eng. 2005;33(6):829-40.
28. Saul KR, Hu X, Goehler CM, Vidt ME, Daly M, Velisar A, et al. Benchmarking of dynamic simulation predictions in two software platforms using an upper limb musculoskeletal model. Comput Methods Biomech Biomed Engin. 2015;18(13):1445-58.
29. McFarland DC, McCain EM, Poppo MN, Saul KR. Spatial Dependency of Glenohumeral Joint Stability During Dynamic Unimanual and Bimanual Pushing and Pulling. J Biomec Eng. 2019;141(5):051006.
30. Seth A, Dong M, Matias R, Delp S. Muscle Contributions to Upper-Extremity Movement and Work From a Musculoskeletal Model of the Human Shoulder. Frontiers Neurorobotics. 2019;13:90.
31. Upper Extremity Dynamic Model. Avaiable at: https://simtk.org/projects/upexdyn. Accessed on 14 April, 2024.
32. De Groot JH, Brand R. A three-dimensional regression model of the shoulder rhythm. Clin Biomech (Bristol, Avon). 2001;16(9):735-43.
33. Millard M, Uchida T, Seth A, Delp SL. Flexing computational muscle: modeling and simulation of musculotendon dynamics. J Biomech Eng. 2013;135(2):021005.
34. Thelen DG. Adjustment of muscle mechanics model parameters to simulate dynamic contractions in older adults. J Biomech Eng. 2003;125(1):70-7.
35. Lund ME. The AnyBody Managed Model Repository (AMMR)," Zenodo. 2017.
36. Veeger HE, Van der Helm FC, Van der Woude LH, Pronk GM, Rozendal RH. Inertia and muscle contraction parameters for musculoskeletal modelling of the shoulder mechanism. J Biomech. 1991;24(7):615-29.
37. Van der Helm FC, Veeger HE, Pronk GM, Van der Woude LH, Rozendal RH. Geometry parameters for musculoskeletal modelling of the shoulder system. J Biomech. 1992;25(2):129-44.
38. Winter DA. Anthropometry in Biomechanics and Motor Control of Human Movement. 2009;82-106.
39. "Muscle Models." Avaiable at: https://anyscript.org/tutorials/Muscle_modeling/lesson5.html#. Accessed on 14 April, 2024.
40. Hicks JL, Uchida TK, Seth A, Rajagopal A, Delp SL. Is my model good enough? Best practices for verification and validation of musculoskeletal models and simulations of movement. J Biomech Eng. 2015;137(2):020905.
41. Basmajian JV, Latif A. Integrated Actions and Functions of the Chief Flexors of the Elbow: A Detailed Electromyographic Analysis. JBJS. 1957;39(5):1106-18.
42. Wattanaprakornkul D, Halaki M, Boettcher C, Cathers I, Ginn KL. A comprehensive analysis of muscle recruitment patterns during shoulder flexion: An electromyographic study. Clin Anatomy. 2011;24(5):619-26.
43. Chang LR, Anand P, Varacallo M. Anatomy, Shoulder and Upper Limb, Glenohumeral Joint. U.S. National Library of Medicine. 2023.
44. Betts JG, Desaix P, Johnson E, Korol O, Kruse D, Poe B, et al. Anatomy and Physiology 2e. OpenStax, 2022.
45. Lam JH, Bordoni B. Anatomy, Shoulder and Upper Limb, Arm Abductor Muscles in StatPearls. Treasure Island (FL): StatPearls Publishing Copyright © 2024, StatPearls Publishing LLC. 2024.
46. Escamilla RF, Yamashiro K, Paulos L, Andrews JR. Shoulder Muscle Activity and Function in Common Shoulder Rehabilitation Exercises. Sports Med. 2009;39(8):663-85.
47. Seth A, Dong M, Matias R, Delp S. Muscle Contributions to Upper-Extremity Movement and Work From a Musculoskeletal Model of the Human Shoulder. Front Neuroro bot. 2019;13:90.

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