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Upper-limb movement analysis – A comparison between two OpenSim models

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Abstract

In-vivo internal structural loads and muscle activation are complex to be performed, but these are crucial for quantitative evaluation of human movements. Hence some musculoskeletal models have been developed in the last decade which provide non-invasive estimations the body movements in normal conditions. Abnormal movements following injuries were simulated using biomechanical model in some previous studies. This study analysed upper limb movements by using a developed upper-extremity OpenSim model which includes strain-adjustable ligaments of the acromio-clavicular joint. In addition, movements analyzing results from using an available model developed from OpenSim community was used for comparison. The upper limb movements used for this research were recorded from two healthy participants. Shoulder range of motion resulted from the developed model and the available model are compared. The results from this comparison suggest that the proposed OpenSim model can be used for upper-limb motion analysis and evaluation.

Keywords*: Musculoskeletal model, upper limb biomechanics, shoulder movement*

Abbreviations

AC	acromioclavicular
DOF	degree-of-freedom

Tóm tắt

Để đánh giá định lượng các chuyển động của cơ thể người, giá trị momen tải ở mỗi khớp và kích thích cơ rất ở mỗi khớp là rất quan trọng, nhưng cũng rất phức tạp để thực hiện đối trực tiếp với cơ thể người. Do đó, trong vài năm gần đây một số mô hình cơ-xương-khớp đã được phát triển nhằm cung cấp các ước lượng về chuyển động của cơ thể người trong điều kiện bình thường. Các nghiên cứu trước đây cũng từ đề cập đến việc ước lượng chuyển động con người trong điều kiện sau chấn thương được mô phỏng bằng mô hình cơ-sinh học. Trong bài báo này, tác giả phân tích các chuyển động của cánh tay bằng cách sử dụng mô hình được phát triển bằng phần mềm OpenSim, mô hình có bổ sung các dây chằng ở xương đòn có thể điều chỉnh được sức căng. Ngoài ra, kết quả phân tích chuyển động bằng một mô hình khác được phát triển từ cộng đồng OpenSim trên thế giới đã được sử dụng để so sánh. Các chuyển động cánh tay được sử dụng trong bài báo này được ghi lại từ hai người khỏe mạnh. Phạm vi chuyển động của cánh tay thu được từ mô hình OpenSim do nhóm tác giả phát triển và mô hình trước đây được phân tích và so sánh. Kết quả so sánh cho thấy mô hình OpenSim được nhóm tác giả phát triển có thể được sử dụng để phân tích và đánh giá chuyển động của cánh tay, ứng dụng trong việc hỗ trợ đánh giá sự phục hồi của người bệnh sau vật lý trị liệu.

1. Introduction

The knowledge of human movement kinematic is a high-value information in biology and rehabilitation research. Functional movement evaluation can be performed under normal or abnormal conditions [1]. However, in-vivo measurements of internal structural loads and muscle activation during human movement are difficult and complex to be performed. Finding another solution to get these valuable information by a non-invasive method are needed. In the last decade, musculoskeletal models were proposed for this issue. The musculoskeletal models which were developed with the human bone anatomy, and muscles' characteristics can provide meaningful estimations of the needed information on human movement.

Human upper limb has perfect anatomy that designed to give us a high mobility and functional movements. The upper limb can be divided into three regions: upper arm, forearm, and hand [2]. The main movements of the upper limb are: shoulder flexion-extension, shoulder abduction-adduction, shoulder medial-lateral rotation, elbow flexion-extension. In daily life, lack of movement function of upper limb can lead to the limitation of activities of daily living, as well as other mobility demands. Hence, understanding the kinematics of upper limb movement is essential for proper rehabilitation training, especially during functional training.

In the recent years, several upper limb musculoskeletal models have been developed using OpenSim software (National Central for Simulation in Rehabilitation Research NCSRR, Stanford, CA, USA) [3]–[8]. For rehabilitation purpose, a shoulder complex skeletal model was developed using a spatial hybrid mechanism, this model was based on joint geometric constraints [9]. There are two main fundamental benefits from using OpenSim software in movement analysis: OpenSim software can calculate variables which are difficult to measure in-vivo, and it can predict movement from models of motor control [10].

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The musculoskeletal models are mainly used to analyse in detailed biomechanical movement. Although, in some studies, the musculoskeletal models were also used to analyse the abnormal movement in which the body was affected by physical injuries. The AnyBody shoulder model was used to investigate the impact of cuff tear arthropathy on the mechanics of the deltoid during elevation in the frontal, scapular and sagittal planes [11]. A previous study performed the simulations on surgical rotator cuff repair of the supraspinatus muscle–tendon unit on upper-extremity using the Stanford VA upper limb model [12]. Recently, evaluating the effects of a change in morphological structure in movement by using the musculoskeletal model has been becoming rather common, and this approach can be a promising reliable and valid method for movement analysis.

In this study, we used a developed OpenSim biomechanical upper limb model in which the model was included acromioclavicular (AC) joint ligaments [13]. The detail description of the model can be found in the previous study [13]. The AC joint ligaments added to this biomechanical model was first intended to estimate the motion kinematics of the shoulder according to different types of Rockwood AC dislocation. In addition to estimate the motion kinematics in abnormal condition, this model was used to analyse the upper limb movement in the normal condition in this work. Data recorded from two healthy young volunteers during moving their upper limb were analysed by this OpenSim model. An available upper limb model developed from OpenSim community – the Wu shoulder model was used for comparison [14]. Shoulder range of motion resulted from these two models are analysed in this work.

2. Main body

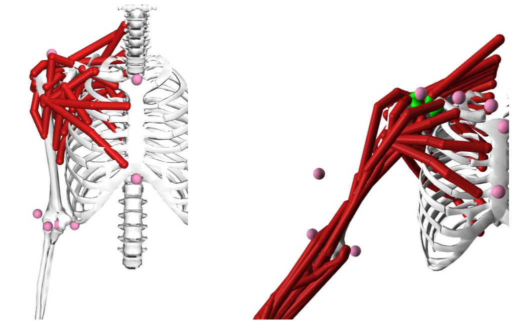
2.1. Materials and methods

2.1.1. *Developed upper limb model*

The detail description of developing the model can be found in our previous study [13]. The model includes 7 degrees of freedom (DOFs), i.e, shoulder rotation/elevation/plane elevation, elbow, forearm and wrist flexion/deviation, and fifty musculo-tendon actuators across these joints. The model was developed based on the anthropometry and muscle force-generating characteristics of a 50th percentile adult male. For the AC joint, three ligaments arranged around were added. In addition, the trapezius muscle was added, as the result, the model was formed with 63 muscle-tendon units in total.

2.1.2. *Wu shoulder model*

The shoulder model used in the work of Wu is a generic 5-segment, 10 degree-of-freedom (DOF) musculoskeletal model of the upper limb which was also developed in OpenSim [14]. 26 Hill-type muscle-tendon units was included in the model, which represent the major axioscapular, axiohumeral and scapula-humeral muscle groups.



a) Wu shoulder model b) Developed model

Figure 1: Upper limb model.

In this model, the forearm and wrist were modelled as one rigid segment that articulated with the elbow via a 2-DOF universal joint. The forearm and wrist segment in our model was modeled independently as a 2-DOF universal joint for each segment.

2.1.3. *Experimental upper limb movement data recording*

Two healthy young volunteers (one female and one male) were instructed to perform right upper limb movements including: upper limb abduction-adduction, upper limb flexion-extension, upper limb horizontal abduction/adduction and hand to mouth. Before enrolled in this work, all the included participants do not have any shoulder surgery, their upper-limb was all in normal condition.

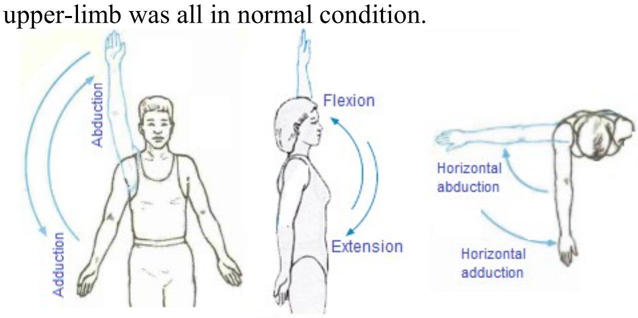


Figure 2: Experiment of upper limb movement performing.

The participants was asked to perform five times for each movement with a self-paced velocity (e.g., they was suggested to count from 1 to 4 while bringing the hand toward the mouth and count from 4 to 1 while returning to the original position). The body landmarks of each participant' upper-limb were marked by the reflective marker. Placing these markers on the body was performed according to the recommendations from a previous study [15].

Table 1: Participants characteristics

	Participant 1	Participant 2
Gender	Female	Male
Height (cm)	156	155
Weight (kg)	46	51
Clavicle (cm)	14	15
Humerus (cm)	24	24
Ulna(cm)	21	23.5

For recording 3D movements, a motion capture system (SMART-DT, BTS Bioengineering Corp., Milano, Italy)

was used to record all the trials. The recording rate was determined at the default setup, 100 frames per second. The movement of each joint in the upper-limb model were extracted using the data recorded form the 3D position of the markers recorded.
The participant characteristics are reported in Table 1.

(a) (b)

Figure 3: Able-bodied subject with markers applied in resting position in anterior (a) and lateral (b) view [13].

2.1.4. *Data analysis*

Since the Wu shoulder model included different marker with our developed model, the position of the markers in the Wu shoulder model has been adjusted to the same position of these in our model.
The models used in this study are generic musculoskeletal model, to make them match the anthropometry of a particular participant, scaling OpenSim tool are used. In OpenSim, the scaling step adjusts both the mass properties (mass and inertia tensor), as well as the dimensions of the body segments.
The inverse kinematics OpenSim tool was used to find each joint angles of the upper-limb model that reproduce the experimental kinematics of a particular participant with the lowest error. In each recorded frame of motion, the marker positions was extracted. Then, this data were imported and used to compute the set of joint angles that make the model in a position that match the experimental kinematics.
Finally, the forces and moments of the joints that produce the movement were estimated by the inverse dynamics OpenSim tool. Performing inverse dynamics require the estimation of mas and inertia of the body and each part of the body. This estimation was performed by the software automatically by the scaling tool.

2.2. Results

From the generic model, each participant's model were scaled using the Scale tool. The error from this process was reported in the Table 2. The RMS marker errors from the developed model were less than 0.02 m, those from the Wu model were between 0.02 m and 0.03 m. Both models result in acceptable error.

Table 2: Scaling results

Model	Partici-pant No.	Total squared error	RMS marker error (m)	Max marker error (m)	Marker with max error
Developed model	1	0.0035	0.0147	0.0240	IJ
	2	0.0044	0.0166	0.0275	DM2
Wu model	1	0.0144	0.0300	0.0540	AA
	2	0.0072	0.0212	0.0319	HDBAR

The elbow-flexion and elbow pronation-supination of two participants against time during the upper limb hand to mouth movement are shown in Figure 4 and Figure 5. As observed in these figures, the joint patterns resulted from two models are the same. The difference between two models are not significant, this demonstrates that the movements were extracted from both models are nearly the same.

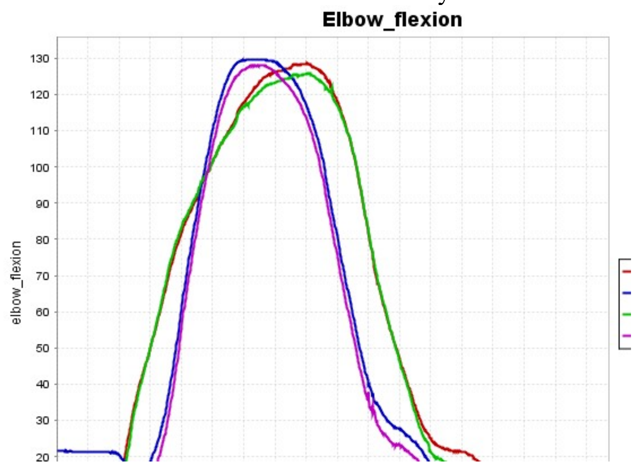


Figure 4: Elbow flexion (in degrees) of two participants plotted against time (in seconds) during hand to mouth movement. (Sx_Wu: Participant x with Wu model; Sx_Self: Participant x with developed model).

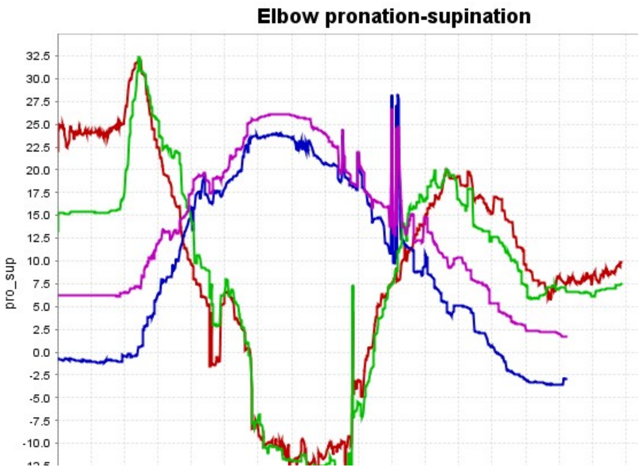


Figure 5: Elbow pronation-supination (in degrees) of two participants plotted against time (in seconds) during hand to mouth movement. (Sx_Wu: Participant x with Wu model; Sx_Self: Participant x with developed model)

The moment at elbow-flexion and elbow pronation-supination joints of two participants against time during the upper limb hand to mouth movement are shown in Figure 6 and Figure 7. As observed in these figures, the joint moments resulted from two models are significant different. This could be the result from the different in body mass of each participant estimated by two models are not the same.

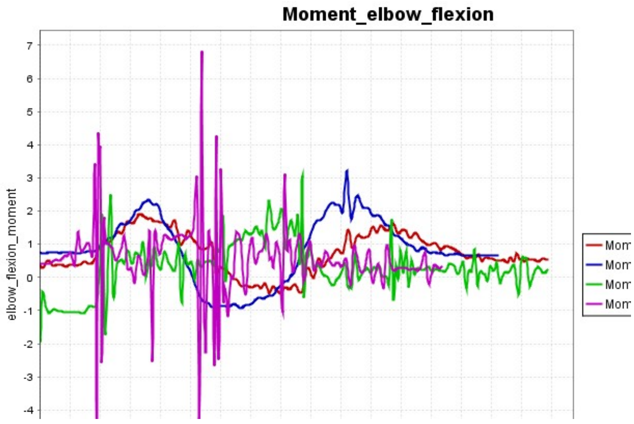


Figure 6: Moment at elbow flexion joint of two participants plotted against time (in seconds) during hand to mouth movement. (Sx_Wu: Participant x with Wu model; Sx_Self: Participant x with developed model)

Figure 7: Moment at elbow pronation-supination joint of two participants plotted against time (in seconds) during hand to mouth movement. (Sx_Wu: Participant x with Wu model; Sx_Self: Participant x with developed model)

The maximum and minimum of elbow flexion and elbow pronation supination during shoulder movements are shown in Table 3. Although there are some slight difference between two models, the trends of these variables can be observed.

2.3. Discussion

During hand to mouth movement, the trend of upper limb joints resulted from two models across time is homogeneous. Although some variability in angle following time can be observed in Figure 4 and Figure 5, but the shape are the same. The reason can be the participants performed the movement with different speed, for example they performed the movement faster in the next time because of muscle fatigue.

The upper limb range of motion were investigated in the previous research [16], and they may effected by gender, age or body mass index. Since this study aims to analyze shoulder movement only, we enrolled only two participants. The detail analysis of the influence of age and gender or body mass on upper limb range of motion are not investigated in this study.

Table 3: Range of joint angle during shoulder movement for two participants

Upper limb movement	Joint angle	
	Elbow flexion	Elbow pro-sup
Adduction-adduction		
Developed model	12.2 – 41.5	-5.1 – 55.3
Wu model	17.3 – 44.4	-4.5 – 66.9
Flexion-extension		
Developed model	16.5 – 49.5	-24.2 – 3.8
Wu model	20.4 – 56.4	-21.3 – -2.7
Horizontal abduction-adduction		
Developed model	0.8 – 12.4	23.6 – 37.5
Wu model	2.5 – 19.2	16.6 – 32.1
Hand to mouth		
Developed model	5 - 129	-17.5 – 32.4
Wu model	11 - 130	-14.7 – 31.9

The two OpenSim models provided quantitative information of upper limb movement kinematics. The Wu shoulder model had been developed and widely used in the OpenSim community. It has been also used for upper limb movement analysis in the literature. In another word, the Wu shoulder model has been proven to be a good model. So that, the comparison between the developed model with the Wu model which result in the same result can emphasize the scientific meaning of this model [17], [18]. The enrolled participants are only healthy participants. Further work can be the movement analysis of abnormal participants or with the patient who got upper limb surgery.

The upper limb range of motion in healthy participants was investigated in several previous studies [16], [17]. The results in our study showed that the range of elbow-flexion during hand to mouth movement from developed model and Wu model are 5 – 129 and 11 – 130, respectively. The results from both two models are consistent with the results using a universal goniometer [16], an electromagnetic tracking device [17]–[19]. This suggests that instead of using the expensive and complex devices, an useful alternative method for upper limb movement analysis can be using the OpenSim model and camera system.

This study consist of some limitations, i.e, the shortage of enrolled participants. To perform comparing the results of upper limb movement in term of gender or age, a comparable number for both male and female participant, and at different range of age should be included in the future experiments. The possible difference between genders or age when performing upper-limb movement can be significant.

3. Conclusion

With the experimental data recorded from two healthy participants, the upper limb movement kinematics were analysed by two OpenSim models. Both models resulted in the same shoulder range of motions. In addition, these results are consistent with the range of shoulder motion in the literature. The results from this comparison suggest that the proposed OpenSim model can be used for upper limb movement analysis and evaluation. Movement analysis using this model in combination with assessment by means of kinematic parameters may provide more detail evaluation of the upper-limb or shoulder movement, which is one of the fundamental elements in health-care research.

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References

[1] K. N. An and E. Y. Chao, "Kinematic analysis of human movement.," *Ann. Biomed. Eng.*, vol. 12, no. 6, pp. 585–597, 1984.

[2] L. J. Forro SD, Munjal A, *Anatomy, Shoulder and Upper Limb, Arm Structure and Function*. In: StatPearls [Internet]. Treasure Island (FL): StatPearls Publishing. Available at: https://www.ncbi.nlm.nih.gov/books/NBK507841/.

[3] S. L. Delp *et al.*, "OpenSim: Open source to create and analyze dynamic simulations of movement," *IEEE Trans. Biomed. Eng.*, vol. 54, no. 11, pp. 1940–1950, 2007.

[4] K. R. S. Holzbaur, W. M. Murray, and S. L. Delp, "A model of the upper extremity for simulating musculoskeletal surgery and analyzing neuromuscular control," *Ann. Biomed. Eng.*, vol. 33, no. 6, pp. 829–840, 2005.

[5] B. A. Garner and M. G. Pandy, "Musculoskeletal Model of the Upper Limb Based on the Visible Human Male Dataset," *Comput. Methods Biomech. Biomed. Engin.*, vol. 4, no. 2, pp. 93–126, 2001.

[6] D. Blana, J. G. Hincapie, E. K. Chadwick, and R. F. Kirsch, "A musculoskeletal model of the upper extremity for use in the development of neuroprosthetic systems," *J. Biomech.*, vol. 41, no. 8, pp. 1714–1721, 2008.

[7] C. R. Dickerson, D. B. Chaffin, and R. E. Hughes, "A mathematical musculoskeletal shoulder model for proactive ergonomic analysis.," *Comput. Methods Biomech. Biomed. Engin.*, vol. 10, no. 6, pp. 389–400, 2007.

[8] M. Damsgaard, J. Rasmussen, S. T. Christensen, E. Surma, and M. de Zee, "Analysis of musculoskeletal systems in the AnyBody Modeling System," *Simul. Model. Pract. Theory*, vol. 14, no. 8, pp. 1100–1111, 2006.

[9] S. Zhibin, M. Tianyu, N. Chao, and N. Yijun, "A New Skeleton Model and the Motion Rhythm Analysis for Human Shoulder Complex Oriented to Rehabilitation Robotics," *Appl. Bionics Biomech.*, vol. 2018, 2018.

[10] A. Seth *et al.*, "OpenSim: Simulating musculoskeletal dynamics and neuromuscular control to study human and animal movement," *PLoS Comput. Biol.*, vol. 14, no. 7, pp. e1006223–e1006223, Jul. 2018.

[11] P. O. Lemieux, N. Nuño, N. Hagemeister, and P. Tétreault, "Mechanical analysis of cuff tear arthropathy during multiplanar elevation with the AnyBody shoulder model," *Clin. Biomech.*, vol. 27, no. 8, pp. 801–806, 2012.

[12] K. R. Saul, S. Hayon, T. L. Smith, C. J. Tuohy, and S. Mannava, "Postural dependence of passive tension in the supraspinatus following rotator cuff repair: A simulation analysis," *Clin. Biomech.*, vol. 26, no. 8, pp. 804–810, 2011.

[13] T. V. Do, P. Dario, T. M. Son, and S. Mazzoleni, "An Approach of Shoulder Movement Analysis Using OpenSim Software," *2019 Int. Conf. Syst. Sci. Eng.*, pp. 511–516, 2019.

[14] W. Wu, P. V. S. Lee, A. L. Bryant, M. Galea, and D. C. Ackland, "Subject-specific musculoskeletal modeling in the evaluation of shoulder muscle and joint function," *J. Biomech.*, vol. 49, no. 15, pp. 3626–3634, 2016.

[15] G. Wu *et al.*, "ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion - Part II: Shoulder, elbow, wrist and hand," *J. Biomech.*, vol. 38, no. 5, pp. 981–992, 2005.

[16] H. Gill, L. Gustafsson, L. Hawcroft, and K. McKenna, "Shoulder joint range of motion in healthy adults aged 20 to 49 years," *Br. J. Occup. Ther.*, vol. 69, no. 12, pp. 556–561, 2006.

[17] Y. Blache, B. Michaud, I. Rogowski, K. Monteil, and M. Begon, "Sensitivity of Shoulder Musculoskeletal Model Predictions to Muscle–Tendon Properties," IEEE Trans. Biomed. Eng., vol. 66, no. 5, pp. 1309–1317, 2019.

[18] W. Wu et al., "Modulation of shoulder muscle and joint function using a powered upper-limb exoskeleton," J. Biomech., vol. 72, pp. 7–16, 2018.

[19] S. Namdari *et al.*, "Defining functional shoulder range of motion for activities of daily living," *J. Shoulder Elb. Surg.*, vol. 21, no. 9, pp. 1177–1183, 2012.

[20] J. MacDermid, K. Sinden, T. Jenkyn, G. Athwal, T. Birmingham, and L. Khadilkar, "An analysis of functional shoulder movements during task performance using Dartfish movement analysis software," *Int. J. Shoulder Surg.*, vol. 8, no. 1, p. 1, 2014.

[21] D. J. Magermans, E. K. J. Chadwick, H. E. J. Veeger, and F. C. T. Van Der Helm, "Requirements for upper extremity motions during activities of daily living," *Clin. Biomech.*, vol. 20, no. 6, pp. 591–599, 2005.