Comfort Analysis in EVA Reachable Envelope Based on Human-Spacesuit Integrated Biomechanical Modeling

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Abstract. We proposed a biomechanical framework for modeling human-spacesuit arm interaction while carrying out EVAs. In the model, there is detailed definition of spacesuit joint rotations, included spacesuit joint stiffness model and a delicate human arm musculoskeletal model in the Anybody Modeling System. The framework is able to predict human joint torque, muscle forces and joint reactions in various positions and postures while wearing spacesuit. Based on the predicted maximum muscle force, we made an evaluation of the comfort scale in various positions in the reach envelope. The predicted most comfortable area was compared to measured most comfortable area for model prediction validation.

Keywords: EVA, spacesuit · Reach envelope · Comfort · Biomechanical modeling

1 Background

Humans have explored the space for decades since Gagarin's first spacewalk and Armstrong's first step on the moon. During the exploration, many missions are conducted through EVAs, such as space station construction and maintenance, scientific experiments and sample collection. As astronauts are faced with extreme environment in space, appropriate protection is necessary by wearing spacesuit. However, the heavy and pressured spacesuit design also restricts the mobility of astronaut, making astronaut working within a smaller envelope and conquering additional resistance to keep posture [1, 2]. Till now, most studies adopt the experimental method of kinematic measure for determining EVA reach envelope and most comfortable area. Only few studies tried using model-based methods to handle work envelope issues. A kinematic model using D-H parameters in robotics and Monte Carlo method is introduced by researchers in ACC (China Astronaut Research and Training Center) to predict EVA work envelope [3]. And the comfort is first evaluated by Schmidt using dynamic modeling method and relative joint torque criterion [4].

Biomechanical modeling method offers a quantified solution to ergonomic assessment of human joint and muscle workload by calculating joint torques and muscle activation [5]. Since there are few studies on comfort analysis in EVA reach

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envelope using biomechanical modeling method, we propose a human-spacesuit integrated modeling method for handling this issue. The predicted reach envelope and its comfort are compared with former experimental results for validation.

2 Method

2.1 Kinematic Model of Spacesuit Arm

Typical kinematic model of spacesuit includes seven joints, which are very similar to the joint definition of human arm, except that the joints in spacesuit arm are in certain serial order and position while some human joints sequence is just defined that way. The joints in the model correspond to certain bearing or soft joint in spacesuit arm. Segments contain spacesuit arm mass, center of mass, moment of inertia and other properties are connected by these joints, as is shown in Fig. 1.

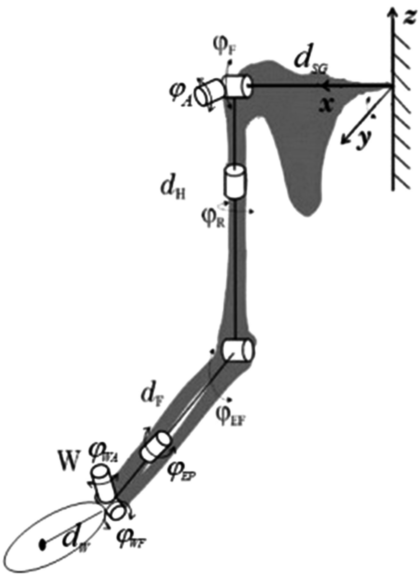


Fig. 1 Kinematic model of spacesuit arm

2.2 Joint Stiffness Measurement and Modeling

Soft-designed joint has a tendency of bounding to its neutral position when it is bent, that is the reason why astronaut in spacesuit has difficulty keeping a non-neutral posture for two long. The tendency is described as joint stiffness which usually works as resistance. Many technique solutions were proposed to measure the joint stiffness, such as RSST (Robotic Space Suit Tester), 'fisher-scale' method and so on. In our study, we used self-motored isokinetic test method to measure spacesuit joint stiffness, which was a working mode in BTE Primus Rehabilitation System and its working theory is the same as 'fish-scale' method except that it bends spacesuit joint automatically.

The measured stiffness shows hysteresis characteristics, which follows different trajectory for flexion and extension, as in shown in Fig. 2. We proposed using neural network optimized Preisach hysteresis model to describe the stiffness that is related to both the current joint angle and angle histories. Because angle histories were not available for comfort analysis, we adopted a simplified three-order polynomial regression to model hysteresis. The stiffness model defined the dynamic property of spacesuit joint.

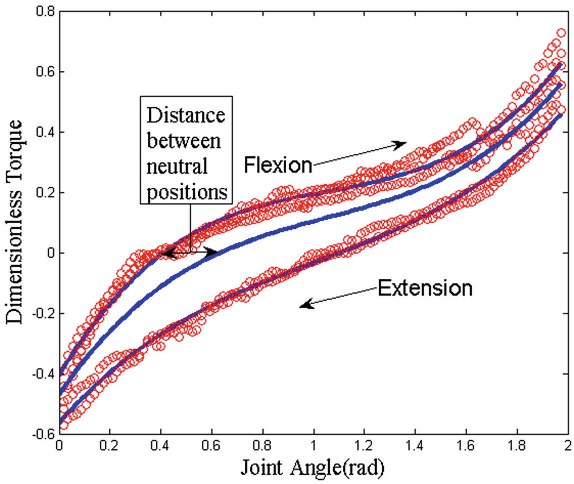


Fig. 2 Hysteresis of elbow joint stiffness

2.3 Human Musculoskeletal System Modeling

We modeled the human arm musculoskeletal system in AnyBody using available bone, joint, muscle and joint reaction definitions [6]. These definitions were based on hundreds of anthropometric and anatomic researches of human musculoskeletal system. We utilized Hill type three-element muscle model to describe the feature that muscle capability changes with muscle length and contracting velocity. As human musculoskeletal system is a redundant system that is believed to contract muscles in an optimal way, we chose the criterion that minimizes that maximum muscle activation as the optimization goal for the inverse dynamic analysis. Considering that the muscle with the maximum activation is most inclined to be fatigued, the criterion postpones muscle fatigue at most. Finally, the inverse dynamic analysis solved all the muscle forces and joint reactions using optimization methods.

2.4 Human Spacesuit Arm Integration

We implemented human spacesuit arm integration using the methods widely used in interface modeling between human and exoskeleton [7]. The integration can be divided into two parts: kinematic and dynamic integration.

In kinematic integration, human hand and spacesuit glove were connected by fixed soft joint which constrains six degrees of freedoms. Human and spacesuit elbow position were also constrained to make sure that human elbow and spacesuit elbow center stay close. Soft joint was included because it allows minimal error which simulates the contact between spacesuit and human skin. By kinematic integration, spacesuit arm moves consistently with human arm.

Astronaut moves spacesuit arm with his own arm by reaction forces between each other, and this is what dynamic integration does. Virtual muscles were introduced to form the reaction element, which works like reaction forces. This method was recently used for predicting reaction forces between foot and ground in gait analysis [8]. Virtual muscles were also included in the inverse dynamic analysis as unknown forces like other muscles. A main difference between virtual muscles and other muscles is that their force capabilities are large so that the optimization algorithm handles them inferior to other muscles. Generally speaking, the algorithm can be divided into two steps for understanding: firstly, find the reaction combination that will produce the minimal activation; secondly, find the muscle activation combination that is minimal.

2.5 Comfort Criteria

In our study, we chose muscle activation and relative joint torque as our comfort criteria. It has been proved that endurance time inclines as muscle load declines. And endurance time changes little after arriving at a typical load between ten and twenty percent of muscle strength, which can be seen as a threshold for comfort. And this percent definition is exactly muscle activation. As maximum muscle activation is the bottleneck and it determines comfort, we chose it as our criterion.

2.6 Reach Envelope and Comfort Prediction

Based on the integrated biomechanical model, we traversed all the arm postures according to the kinematic model of spacesuit arm and its joint RoM. In the simulation, average parameters of subjects such as muscle strength scale, height, weight, upper arm and lower arm length were adopted. The joints included in traverse included φ_F, φ_A, φ_R and φ_{EF} as these joints determine the position of hand while other joints only change hand orientation and position little. The resolution is set to 10° for all the joint angles. A total of over 10000 postures were evaluated using the integrated model, returning the hand position, maximum muscle activation and joint torques of shoulder, elbow and wrist joint. With these data, we determined which space was reachable and then determined the minimal muscle activation index and minimal composite index based on relative joint torque. Reach envelope was then modified by collision detection and elimination between suit glove and spacesuit trunk. Minimal index in a space was chosen because there are several postures for a given space or even give point, among these astronauts will choose the most comfortable one automatically. Finally, comfort was evaluated with the minimal criterion index.

3 Experiment

3.1 Subjects

Nine subjects participated in the reach envelope and comfort evaluation experiment with height of 172±7 cm and weight of 70±12 kg

3.2 Data Collection

Reflective markers were placed on spacesuit glove for hand position capture with NDI Optotrak when subjects moved horizontally and vertically layer by layer in the reachable area. Reach envelope was then determined with the captured positions.

When assessing comfort, subjects were firstly required to give three heights that were comfortable: lowest, medium and highest. For every height, a horizontal supporting bar was placed at a comfortable distance from subjects to relieve the effect of gravity. Subjects were required to move his hand along the bar, finding the most comfortable left and right boundaries.

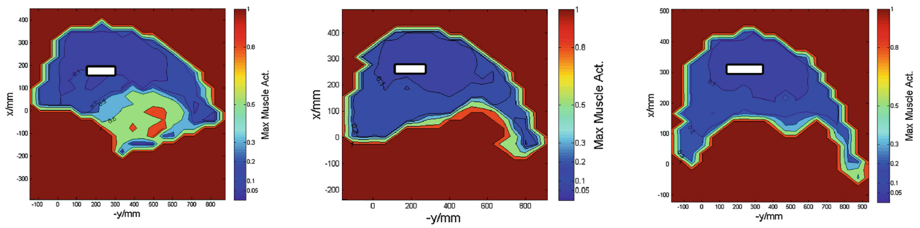
4 Result and Validation

4.1 Comfort Analysis Using Different Criteria

Two different criteria were proposed for comfort assessment, one based on maximum muscle activation and the other based on relative joint torque of the total arm. We compared the result on the horizontal plane where z = 212 mm, as is shown in the following picture. The region in the middle of every figure is the predicted reach envelope. The area with the smaller index is more comfortable compared to those with larger index. It is shown that the comfortable areas using the two different criteria are very close, except that their scales are different.

4.2 Most Comfortable Area Validation

In the experiment, subjects were required to find the most comfortable area on the lowest, medium and highest horizontal plane. After taking an average of the measured areas, we determined the plane where z axis is respectively −82 mm, 34 mm and 200 mm as the lowest, medium and highest horizontal plane. We showed the measured most comfortable area in the comfort contour map predicted using max muscle activation criterion as follows. The measured most comfortable area (white area) was within the predicted most comfortable area which validated the model.



(a)z=-82mm (b)z=34mm (c)z=200mm

Fig. 3 Predicted comfort scale and measured most comfortable area

5 Discussion

Considering that fatigue is usually produced in muscle with maximum activation, max muscle activation criterion is a reasonable physiological comfort scale. Based on the max muscle activation criterion, we compared the predicted comfort contour map and the measured most comfortable area for model validation. The measured most comfortable area is within the predicted most comfortable area. But it is not in the center; instead it is near to the body and goes left. This is reasonable considering that subjects evaluated the comfort not only according to the muscle feeling, but also according to contact feeling of pressure between spacesuit and human arm, which is related to the reaction element used in dynamic integration. The model prediction is closely related to anthropometric parameters in human model, which may differ a little from subjects. Besides, we adopted the regression polynomial of flexion and abduction for the elbow and shoulder respectively in the simulation. However, when subjects moved left and right searching for the most comfortable area, the stiffness trajectory would approach the medium regression as is shown in Fig. 3. So the neutral position where stiffness was zero and usually most comfortable would have a bias of about 12°. All these factors contribute to the offset of the most comfortable area.

6 Conclusion

Human-spacesuit integrated biomechanical modeling is an effective tool for determining reach envelope and comfort in it. Generally speaking, the contributions of our work to ergonomic assessment of spacesuit are summarized as following: firstly, we proposed and realized a complete biomechanical modeling framework for human-spacesuit integration; Secondly, we proposed predicting comfort scale in the reachable envelope using quantified method based on predicted muscle activations instead of subjective ratings alone. The comfort-scale assessment in the reach envelope is just a case illustration of the applicability of human-spacesuit arm integration model in an inverse biomechanical framework. The model can be used for modeling realistic operational tasks when motion data is collected, making work envelope analysis of astronauts in EVAs related to operation. In future, the model is supposed to include detailed surface definition of spacesuit and human skin for more delicate simulation.

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