A Data-Based Modeling Approach of Reach Capacity and Discomfort for Digital Human Models

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Abstract. In this paper, we have proposed a unified data based approach which aims to predict both reach envelops and reach discomfort for a digital human model. Reach envelops can be obtained by applying the existing reach posture data to a new subject according to simulation scenario. Four reach surfaces are proposed according to the radial distance from the shoulder. The discomfort of a target on each surface needs to be defined at first. Then, the discomfort of an intermediate distance between two reach distances is interpolated. The proposed approach is illustrated by the data of a previous study. In this study, 38 young and elderly subjects were instructed to reach 94 targets for each from a seated position, covering a large reachable space.

Keywords: Reach, discomfort, digital human modeling, reach posture.

1 Introduction

For ergonomic design of workplace, most of the studies on arm reach were either limited to the determination of reach envelopes [1-4] or to motion analysis for understanding motion control strategies or/and their simulation [5-8]. Recently, a few investigators studied the discomfort (or difficulty) of arm reach ([9], [10]). The proposed discomfort predictive models were either based on target position or on reach posture (joint angles). Both models cannot take into account maximal reach limits directly, as target location and joint angles are continuous variables and no criteria were defined for testing if a target is out of reach. The predictive models have to be able to differentiate reachable targets from those of out-of-reach. Discomfort evaluation makes sense only for reachable targets. Reach envelopes were studied in the past. But only statistical models for predicting population envelopes were developed. Though they are useful especially for car interior design, they cannot be used for predicting an individual reach capacity in case of DHM (Digital Human Models) applications. In this paper, a unified data based approach for digital human models will be presented for predicting both individual reach envelopes and discomfort of a reachable target.

In order to illustrate the proposed approach, the data from a previous study on seated reach discomfort will be used [10].

V.G. Duffy (Ed.): Digital Human Modeling, HCII 2007, LNCS 4561, pp. 215–223, 2007.

2 Data and Preliminary Analysis

2.1 Data Collecting

Thirty eight subjects participated in the experiment and were paid for it. They were divided in two age groups: 18 young subjects (9 women and 9 men) aged between 20 and 33 years and 20 elderly people (10 women and 10 men) aged between 64 and 76 years. In order to reduce the effects of environment (seat type, cloth, etc…) on reach capacity, the subjects were seated on a flat stool and were asked to push a toggle switch. The seat height was adjusted so that the knees were flexed around 90 degrees. Subjects were strapped on the seat to restrict pelvis motions relative to the seat. They were instructed to reach the toggle switch naturally with the right hand from a same starting position for all targets and then to go back to the starting position. The experimental device is shown in Figure 1. The subjects were asked to keep both arms along the body and the torso upright at the beginning.

Target locations covered a wide workspace within the reaching limits of the subjects:

- 5 plane orientations: -45° (left), 0°, 45°, 90° and 135°
- 5 heights
- 4 distances

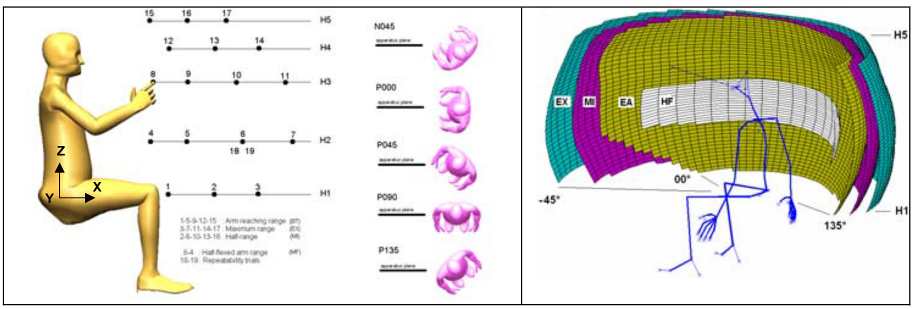

Fig. 1. Target location and illustration of the four reach surfaces of a subject

The five plane orientations were the sagittal plane through the right shoulder (P000), 45° on the left (N045), the planes (P045, P090, P135) 45°, 90° and 135° on the right with respect to P000. Target heights and distances were defined with respect to one's own anthropometry and reach capacity. The five heights were seat height H1, shoulder height H3, mid height between H1 and H3 (H2), height corresponding to an arm elevation of 135° (H5), mid height between H3 and H5 (H4). The four radiale distances were defined with respect to the index fingertip maximum reach distances without (Extended Arm EA) and with (Extreme distance EX) torso participation for each height. MI was the mid distance between EA and EX. HF (Half flexed arm) was defined by subtracting the hand length from EA. Reach distances EA and EX for each height in each orientation plane were determined prior to the experiment for every subject. Due to the interference with the left knee, the target N045-H1-EA was removed. In total, eighty four different positions (17x5-1) were defined. In order to test the repeatability of discomfort rating and movement, the target H2-MI was repeated three times for every plane orientation (6-18-19 in Figure 1). In total, each subject was asked to reach ninety four (94) targets. The trial order was randomly chosen in an orientation plane which was also randomly fixed. Movements were captured using the optoelectronic system VICON. After each reach movement, the subjects were asked to rate the associated discomfort using a slightly modified category partition scale CP-50 [10]. The ratings were ranged from 0 to 50.

To ensure a good quality of motion reconstruction, the markers trajectories provided by VICON were smoothed and missed markers were recovered as much as possible thanks to redundant number of markers. Then, for each subject, a digital model was manually defined by superimposing the model on the subject's photos in a referential posture. The positions of markers in local body segment coordinate systems were identified on the digital model from a referential posture. Finally, joint angles were calculated by inverse kinematics by minimizing the distance between markers positions of the model and measured ones. Refer to the work by Wang et al. [11] and Ausejo et al. [12] for more details. Figure 2 shows an example of reconstructed reach posture with a digital human model.

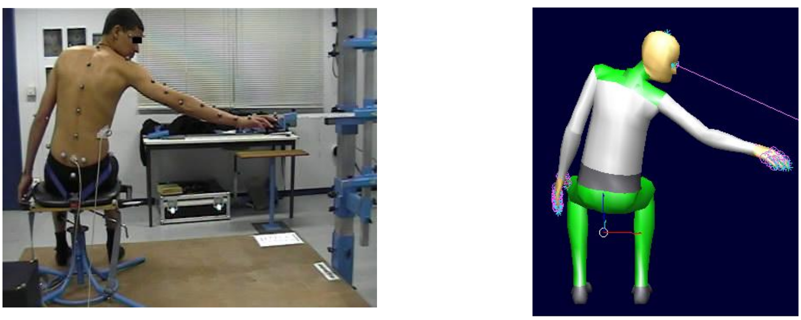

Fig. 2. Real and reconstructed reach postures

2.1 Preliminary Analysis

A preliminary analysis was carried out to examine the effects of age, gender and target location on perceived discomfort (Table 1). Target position was defined in a seat spherical coordinate system centered at the mean shoulder center of the starting postures of all trials. Therefore a target is defined by its longitude (α), latitude (β) and its radial distance (ρ_n) from the shoulder center normalized by the upper limb length (see also Figure 4). From Table 1, one can see that there was a strong effect of age. The gender had negligible effect. As expected, target location had a strong effect. The target latitude and longitude had a strong interaction with age. However, target distance had the same effect for both younger and older groups. This is probably due to the fact that the target distance was defined with respect to one's reach capacity.

In what follows, we will divide the data only according to age group without distinction of the gender.

Table 1. ANOVA table showing effects of age, gender and target location on perceived discomfort of reach posture

Source	Sumof squares	Dof	Mean sq.	Ratio F	Proba.
Age (A)	459.234	1	459.234	6.88	0.0087
Gendre (G)	14.4652	1	14.4652	0.22	*0.6416*
Distance (ρ_n)	34464.9	1	34464.9	516.23	0.0000
Longitude (α)	7081.79	1	7081.79	106.07	0.0000
Latitude (β)	39.6942	1	39.6942	0.59	*0.4407*
A x ρ_n	2.96247	1	2.96247	0.04	*0.8332*
A x α	383.843	1	383.843	5.75	0.0165
A x β	2656.3	1	2656.3	39.79	0.0000
ρ_n x α	926.417	1	926.417	13.88	0.0002
ρ_n x β	943.301	1	943.301	14.13	0.0002
α x β	101.05	1	101.05	1.51	*0.2186*
Residu	224324.	3360	66.763		
Total	391186.	3371			

3 A Unified Reach and Reach Discomfort Modeling Approach

As stated in Introduction, our aim is to propose a unified approach which predicts both reach capacity and reach discomfort for a digital human model. The proposed approach consists of three steps. As it is a data-based approach, the first step is to collect data for both reach postures and discomfort ratings. In order to make discomfort ratings comparable between subjects, target location should be defined with respect to one's anthropometry and reach capacity. Four reach surfaces were defined according to reach distance in our experiment: nearly half flexed distance without moving the torso (HF), extended arm length (EA) without moving the torso, maximum reach distance with torso participation (MX), mid distance (MI) between the distances EA and MX. Once the data are collected, the next step is to structure the data of postures for each of these four reach distances in terms of subject's anthropometric characteristics (sitting height, upper limb length, age, gender, joint mobility …). The database is then used for generating these four reach surfaces for an individual digital human according to simulation scenario. The same method was used for constituting an in-vehicle reach motion database [13]. The third step is to fit the discomfort ratings in terms of target position (longitude and latitude) on each of these four reach envelops using a surface regression fitting method. The discomfort of an intermediate distance between two reach distances will be interpolated (Figure 4). The reason why we fit discomfort ratings on reach envelope instead of target position is that a target distance is judged with respect to one's reach capacity. A far target for a short person is certainly not as far as for a tall person. The short and tall persons will certainly not rate the target in the same way. We believe that the discomfort for a target defined with respect to one's reach surfaces like EA and MX is rated in the same way between different people. This makes it possible to compare the ratings of the subjects of different reach capacity and to reduce the number of variables in the discomfort predictive model.

Figure 3 shows how the proposed approach can be used for simulating a subject's reach envelop as well as his(her) reach discomfort for a target. The basic idea is to re-use the structured database for extracting the reach postures of the most similar subject who participated in the real experiment. As only the posture data are re-used, the four reach envelops are generated by applying these posture data using direct kinematics to the anthropometric dimensions of the virtual subject. Therefore, the anthropometric dimensions are indirectly taken into account for predicting reach capacity and discomfort.

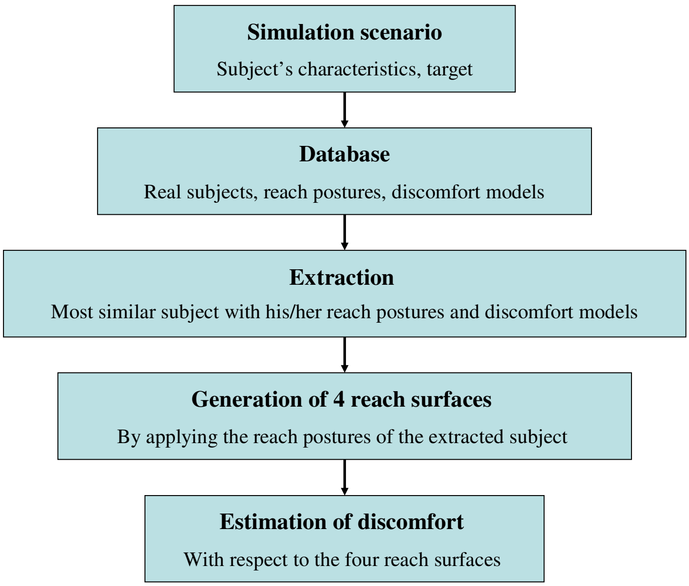

Fig. 3. Application the proposed approach to simulate a subject's reach envelopes and reach discomfort

4 Discomfort Models

In the proposed approach, we need to know how discomfort varies in terms of target position on each of these four reach envelops at first. Then, reach discomfort of a target is obtained by interpolation as function of its distance with respect to the intercepted surfaces (Figure 4). The discomfort models for each reach surface can be obtained using a surface regression fitting method. The aim of model fitting here is to express the discomfort rating as a function of target longitude α and latitude β for a reach surface. The position of zero longitude and zero latitude is defined when the target is located in the frontal plane at the shoulder height (Figure 4). Here the method of surface fitting with orthogonal polynomials was applied to our data. The same method was also used to model the upper arm axial rotation limits [14]. As in [14], a transformation on β is necessary so that the model should not be sensitive to the variation of longitude when the target position is near to the poles $\beta = \pm\pi/2$:

$$x(\alpha,\beta) = \alpha\cos\beta, \quad y(\alpha,\beta) = \beta \tag{1}$$

making the variable x independent of the longitude angle α at the poles. We assume that the discomfort of a target on a reach surface can be described by the following staistical regression model

$$D(\alpha,\beta) = \sum_{j=0}^{k} a_j P_j(x,y) + \varepsilon \tag{2}$$

where P_j is a j-th ordered polynomial basis with two independent variables x and y, k is the highest order of the polynomial basis (the degree of regression) and ε is a normal random error.

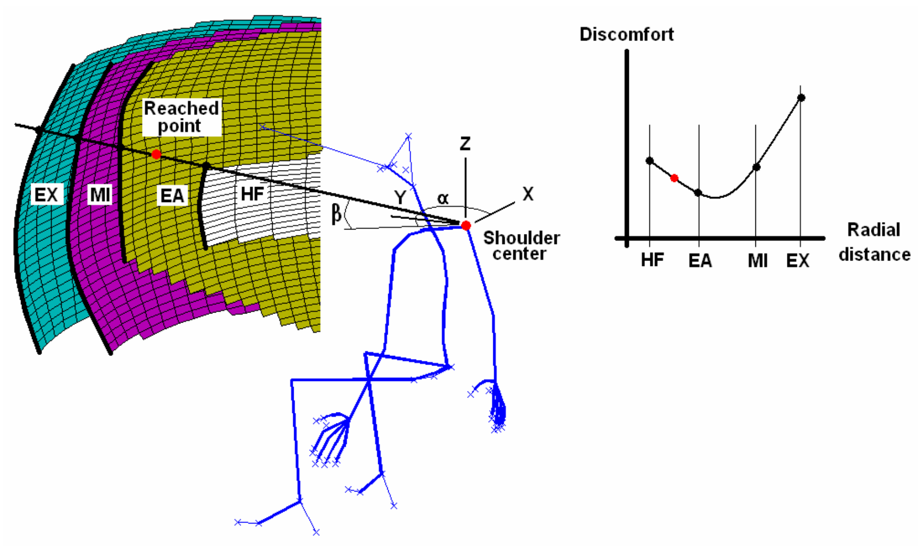

Fig. 4. Estimation of the reach discomfort of a target by interpolation as a function of its distance to the intercepted surfaces

Instead of using a direct polynomial basis, which may suffer from computational complications and may have oscillatory behavior particularly near to the boundary of the data area, an orthogonal homogeneous polynomial basis can be used,

$$P_j(x,y) = \sum_{m=0}^{j} b_{jm} x^{j-m}(\alpha,\beta)\, y^m(\alpha,\beta) \tag{3}$$

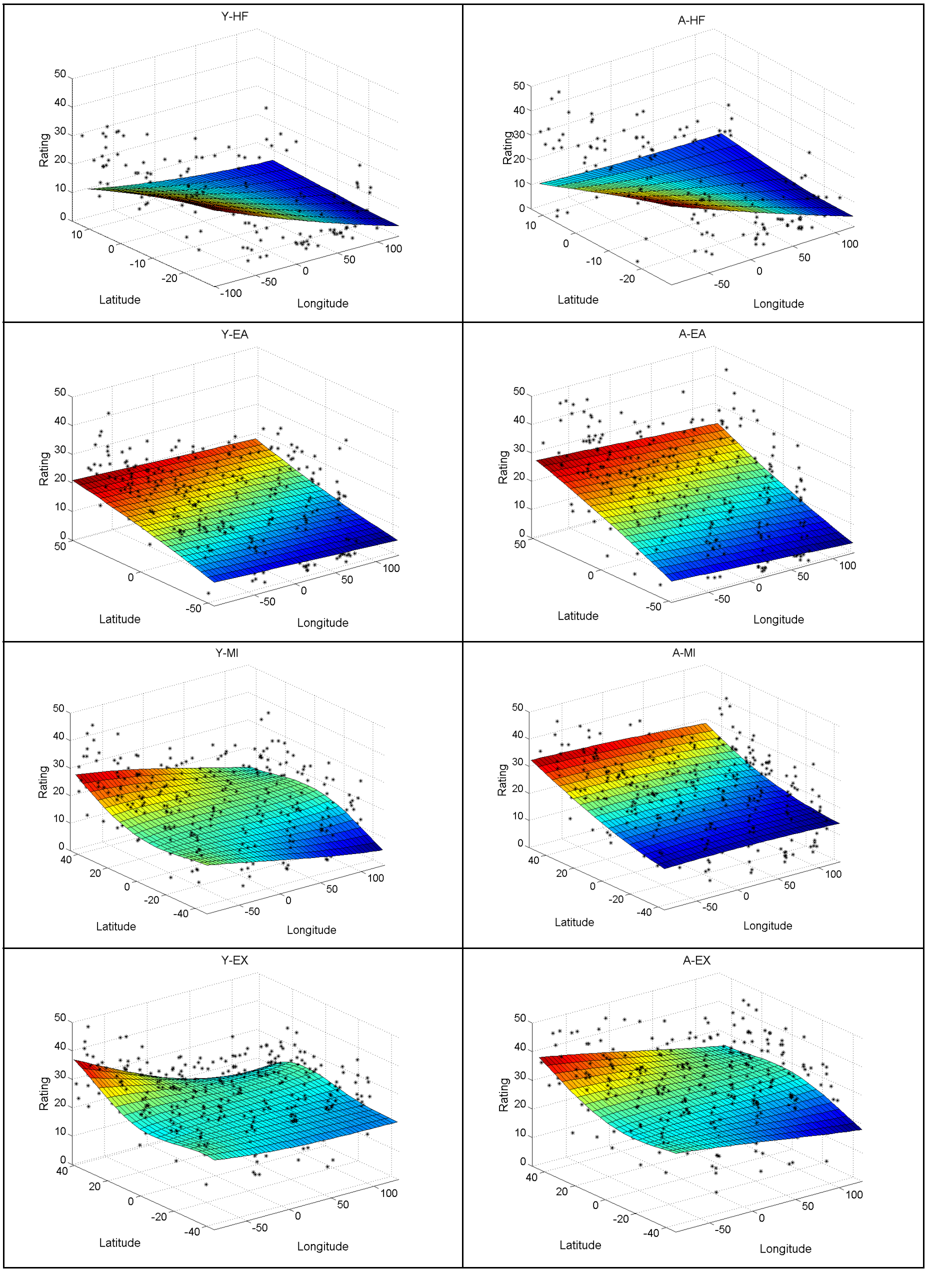

Fig. 5. Modeling of discomfort rating of a target located in 4 reach surfaces (HF, EA, MI and EX). The models for the young subjects (on the left column) and the aged ones (on the right column) are compared.

with b_{j0}=1 for each j and $P_0(x,y)=0$. The following conditions of orthogonality allow the calculation, in a step-by-step way, of the j unknown coefficients b_{j1}, b_{j2}, …, b_{jj} for every P_j ($j \geq 1$) based upon the n pairs of recorded data (α_i,β_i), i=1,2,...,n,

$$\sum_{j=1}^{n} P_j(x_i, y_i) P_m(x_i, y_i) = 0 \text{, m = 0, 1, 2, …, j-1} \quad (4)$$

The coefficients a_j and k in (2) can be determined by classical multiple regression procedure. Refer to [14] for more details.

Figure 5 compares the discomfort models for the 4 reach surfaces. From the preliminary analysis, a strong effect of age group was observed. The data were therefore separated according age groups. In Figure 5, the models for the young and elderly subjects are also compared. One can see that subjects preferred the targets which were located forwardly below the shoulder height, as expected. Notice that there is a slight difference between young and elderly groups for the surfaces MI and EX. The elderly subjects were more sensitive to target latitude.

5 Concluding Remarks

In this paper, we have proposed a unified data based approach which aims to predict both reach envelops and reach discomfort for a digital human model. Like all data based approaches, the prediction depends on the wealth of data. Besides, it depends on how a referential subject is selected from database. In addition to classical anthropometric dimensions, other criteria are required for describing one's characteristics. Clearly, the reach envelops and discomfort of reaching a target depend on one's reach capacity. This should be included in the selection criteria. However, it is difficult to define a global index that can be used for the definition of reach capacity. One solution may be to take all subjects contained in the same age group and to simulate the reach discomfort from these data, thus the inter-individual variability being taken into account. In workplace design, the question often posed is how many percent of target population can reach a control under a certain limit of discomfort rating. This requires the simulation of a population, called 'population simulation'. This concept has been proposed and implemented in our ergonomic simulation software RPx ([13], [15]). The basic idea behind is to generate a representative sample of digital human subjects at first and then to evaluate the overall discomfort based on individual responses using the proposed approach.

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