Generation of the Reach Volume for Design and Evaluation of the Workplaces

(작업장 설계 및 평가를 위한 Reach Volume의 생성)

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ABSTRACT

When designing workplaces, controls should be placed within the reach of operator's arm or foot to guarantee effective performance. The aviation industry is perhaps the chief user of anthropometric data for its need to weight minimization and space optimization. In designing a workplace which must cater to a wide range of operator size, it might be sufficient to plan only for the 'average person'. Static arm reach measurements which are taken in conventional, standardized positions provide the necessary information, but they cannot be directly applied to dynamic situations.

In this research, an approximate algorithm to generate the workspace of the human body including foot reach and trunk motion is proposed and tested. The robot kinematics was employed to represent the human body as a multi-link system.

I. Introduction

When designing workplaces, controls should be placed within the reach of operator's arm or foot to guarantee effective performances. The aviation industry is perhaps the chief user of anthropometric data for its need to weight minimization and space optimization. The automotive industry also requires anthropometric data of dynamic or functional type so that it may improve driver's accommodation [2]. McFarland et al.[9] stressed the difficulty of even recognizing the many factors that may contribute to accidents, but suggested that an immediate and tangible return might be expected from a proper design of the agent or vehicle.

In designing a workplace which must cater to a wide range of operator size, it might be sufficient to plan only for the 'average person' [2]. Static arm reach measurements which are taken in conventional, standardized positions provide the necessary information, but they cannot be directly applied to dynamic situations such as those which exist during operation since few tasks require the human to be rigid and motionless. How far one can reach depends not only on the length of one's arm but also on trunk rotation, shoulder rotation and back bend, etc. Thus, what is needed is a

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dynamic measurement defining a volume of space that can be reached by a certain population [8].

Approaches to determining workspace have been focused on setting up its theoretical foundation and has been the subject of numerous experiments. The range of arm work has beenpresented by many authors in various ways: from simple, one-dimensional systems, so-called reaches, via the two-dimensional ones, e.g., on the vertical or horizontal plane, and the three-dimensional, to more complicated spatial systems [2, 6, 8,10].

However, the methods employed and measuring systems applied differed in the way that comparison and application of the results was difficult to be made. In addition, most of these measurements are related to Caucasian and Chinese populations, and these findings are limited only to arm reach and foot reach have been excluded. Furthermore, these studies did not consider trunk motion (vertebral motion) when measuring arm reach. In real situations, the controls are often operated by foot such as foot pedals in vehicles. Therefore, an investigation is needed which includes trunk motion as well as arm and foot reach.

In this research, an approximate algorithm to generate the workspace of the human body including foot and trunk motion is proposed. The robot kinematics was employed to represent the human body as a multi-link system.

II. Modeling of the Human Body

In this study, the human body is regarded as a multi-link system. Though the human body is provided with hundreds of freedom which give us great flexibility in comparison with most mechanical devices, to simplify the link system of the human body we assumed the following:

1) the human body is divided into two parts: upper and lower body,
2) the upper body is symmetrical with respect to the sagittal plane,
3) the hip joint functions as a virtual joint in upper body, and functions as a real joint in lower limb,
3) the wrist adduction and abduction is minimized during the sequence of reach activities.

2.1. Upper body

The upper body is then divided into two parts; right and left upper body. Each upper body consists of four links - trunk, upper arm, lower arm and hand, and is regarded as a manipulator with eight degrees of freedom, which is composed of three in hip (trunk rotation, trunk lateral bending, and hip flexion) and shoulder joint (flexion, adduction-abduction, and rotation), and one in elbow (flexion) and wrist joint (flexion). All the above joints are assumed to be revolute joints. The link system of right upper body is illustrated in Figure 1.

2.2. Lower Body

The lower body or limb is also divided into two parts-right and left lower limb. Each lower limb consists of three links - upper leg, lower leg, and foot. It is regarded as a manipulator with six degrees of freedom, which is composed of three in hip (flexion, rotation, and adduction-abduction), two in knee (flexion and rotation), and one in ankle (flexion). All the joints of the lower limb are also revolute joints. The link system of right lower limb is illustrated in Figure 2.

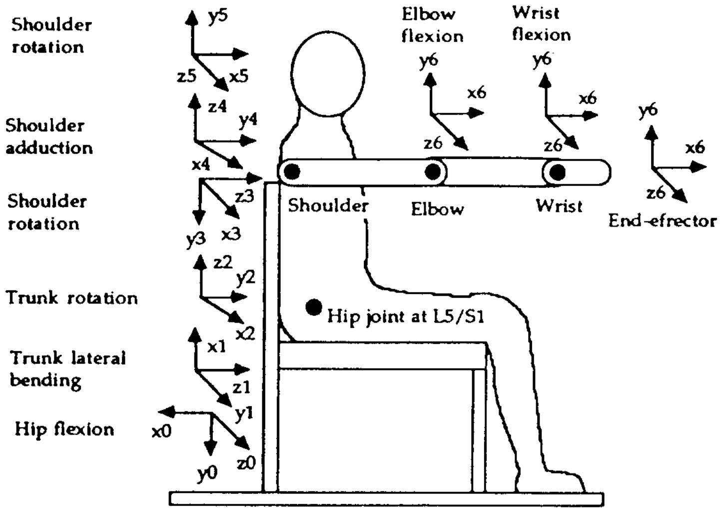

Figure 1. Link system of right upper body

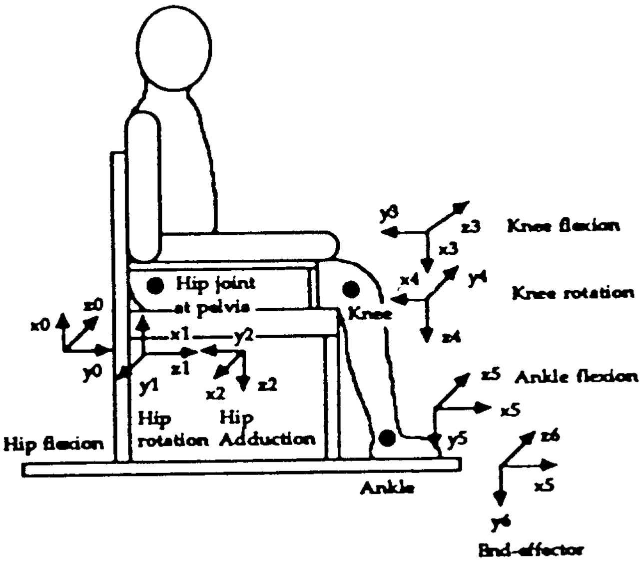

Figure 2. Link system of right lower limb

2.3. Link Parameters of Each Link System

In robotics, to describe the translational and rotational relationships between adjacent links, several kinematic notations have been used to systematically establish a coordinate system (body-attached frame) to each link of an articulated chain : D-H notation [1,4,5], S-U notation [11], SET notation [12], K-Y notation [7], C-Y notation [3]. Among them, the D-H notation was employed to represent the human body, which is very concise since minimum parameters are used.

The relative location of the two coordinate frames are completely determined by the following four parameters (two distance and two angle variables) .

a_i : the length of the common normal

d_i : the distance between the origin O_{i-1} and the point H_i

α_i : the angle between the joint axis i and the z_i axis in the right-hand sense

θ_i : the angle between the x_{i-1} axis and the common normal H_iO_i measured about the z_{i-1} axis in the right-hand sense.

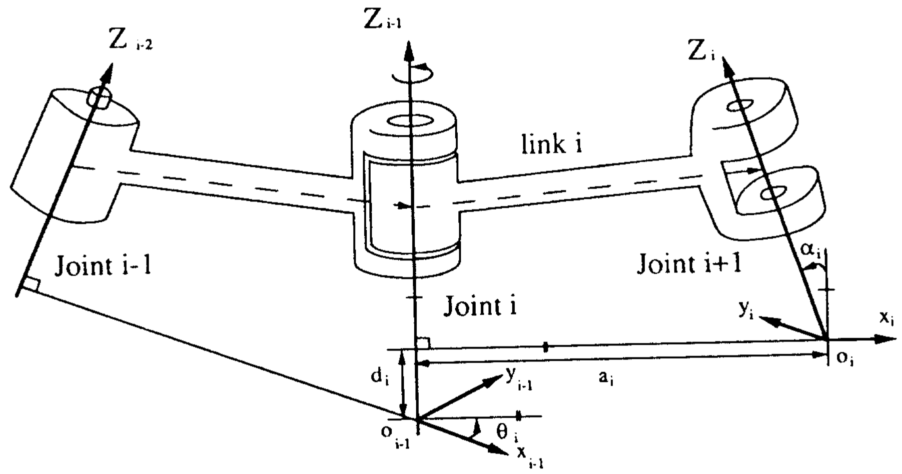

Figure 3. The Denavit-Hartenberg notation

The 4 x 4 homogeneous transformation matrix can be obtained by applying successive rotations and translations to align the frame i-1 with frame i, which yield the following matrix :

$$T_i^{i-1} = \begin{bmatrix} c\theta_i - s\theta_i s\alpha_i & -s\theta_i c\alpha_i & c\theta_i + s\theta_i s\alpha_i & a_i c\theta_i \\ s\theta_i + c\theta_i s\alpha_i & c\theta_i c\alpha_i & s\theta_i - c\theta_i s\alpha_i & a_i s\theta_i \\ - c\alpha_i & s\alpha_i & c\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The parameters of the human body defined in the D-H notation are shown in Table 1. We can obtain the T matrix, $T = T^0_1 \times T^1_2 \times \ldots\ldots \times T^{n-1}_n = T^0_n$, given the values of the four parameters in each joint. This matrix specifies the position and orientation of the endpoint of the manipulator with respect to the base coordinate system.

III. Reach Volume of the Human Body

3.1. Workspace of the Upper Body

Table 1. Four parameters of the human body

(a) Right upper body

Link	α_i	a_i	d_i	θ_i
1	90°	0	0	θ_1
2	90°	0	0	θ_2
3	-90°	0	l_1	θ_3
4	90°	0	0	θ_4
5	90°	0	0	θ_5
6	0°	l_2	0	θ_6
7	0°	l_3	0	θ_7
8	0°	l_4	0	θ_8

* l_1 : length of trunk, l_2 : length of upper arm,
l_3 : length of lower arm, l_4 : length of hand

(b) Right lower body

Link	a_i	d_i	α_i	θ_i
1	0	0	-90°	θ_1
2	0	0	-90°	θ_2
3	0	l_1	-90°	θ_3
4	0	0	90°	θ_4
5	0	l_2	90°	θ_5
6	l_3	0	0°	θ_6

* l_1 : length of upper leg, l_2 : length of lower leg,
l_3 : length of ankle to toe.

According to the assumption defined, the human body is divided into upper and lower body, and again each body into right and left parts with respect to the sagittal plane. Here, two workspaces of right and left upper body are obtained. At the beginning, each link of the upper body -trunk, upper arm, lower arm, and hand- is straightened up, and hip joint is flexed fully. Subsequently, hip joint is laterally bent incrementally, and again hip joint is flexed fully.

The algorithm is as follows, where the link system in Figure 1 is used:

Step 1 Initialize posture
; trunk flexion = -75°
trunk adduction-abduction = 80.79°(99.20°, for left arm)
trunk rotation = 0°
shoulder rotation = 180°
shoulder adduction-abduction = 90°

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            shoulder flexion = 90°
            elbow flexion = 0°
            wrist flexion = 0°
step 2  flex hip joint forward until angle of hip flexion reaches -175°
step 3  if hip adduction-abduction <= 170°
      (limit of range of motion) ( >= 10°, for left arm),
          then hip flexion=-75°,
          hip adduction-abduction=hip adduction-abduction+5,
          (hip adduction-abduction=hip adduction-abduction-5,
                for left arm)
          and go to step 2.
step 4  End
```

The workspace of the upper body is presented in Figure 4.

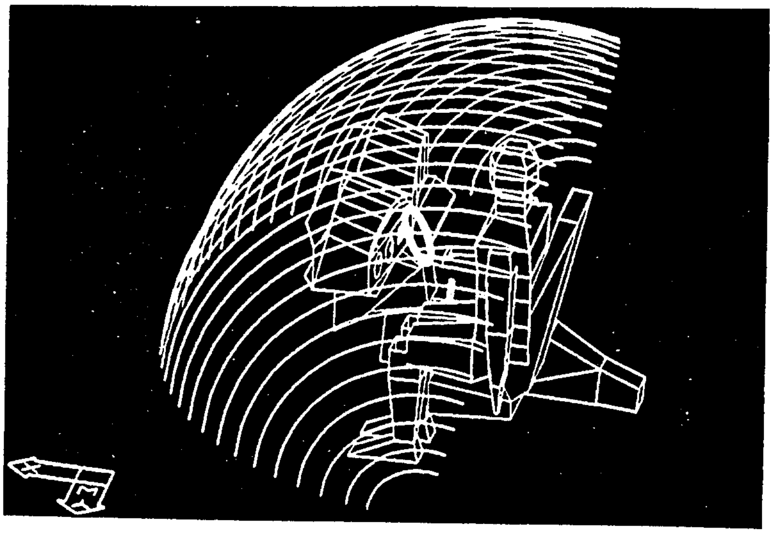

Figure 4. Workspace of the upper body

3.2. Workspace of the Lower Limb

Based on the link system shown in Figure 2, the algorithm to generate workspace for seated operators is developed as follows:

```
Step 1  Initialize posture
          ; hip flexion = -205°
            hip rotation = 90°
            hip adduction-abduction = 100.47°(79.52°, for left leg)
            knee flexion = 0°
            knee rotation = 180°
            ankle flexion = 90°
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step 2  flex hip joint forward until angle of hip flexion reaches -180°
step 3  flex knee joint backward until angle of knee flexion reaches 105°
step 4  if hip adduction-abduction >= 37°(limit of range of motion)
            ( <= 143°, for left leg)
            then hip flexion=-205°,
             hip adduction-abduction=hip adduction-abduction-5,
             (hip adduction-abduction=hip adduction-abduction+5,
                     for left leg)
             and go to step 2.
step 5  End
```

The workspace generated from this algorithm appears in Figure 5.

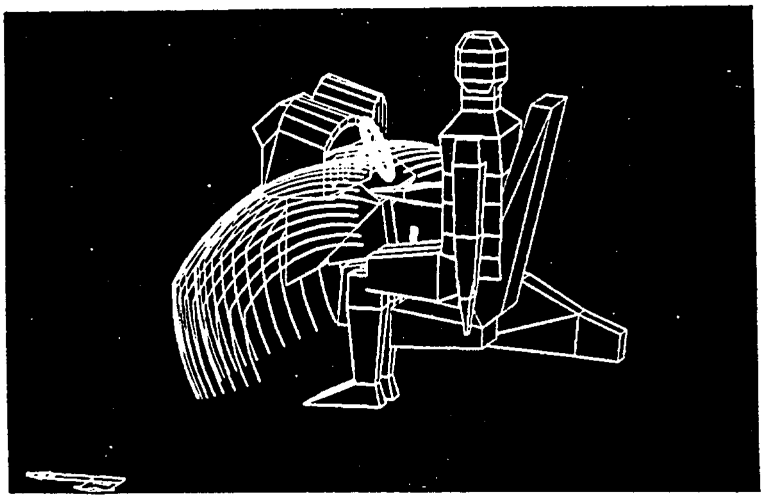

Figure 5. Workspace of the lower limb

IV. Validation of the Workspace

4.1. Subject and Apparatus

One male subject was tested in the experiment for validating the workspace generated in this research. The subject was a graduate student in POSTECH. He showed no physical handicap, and was 169 cm tall and weighed 55 kg.

In this test, the Expert Vision Motion Analysis System was used to obtain the motion trajectory of the subject, where two markers were attached on hip joint and finger tip in the workspace of the upper body, and hip joint and toe tip in the workspace of the lower limb, respectively.

4.2. Test Results

4.2.1. Workspace of the Upper Body

Six angles (positions) in the right side of subject were selected to represent reach area (vertical cross-section of the workspace) of one's workspace. The subject was instructed to straighten up each link of the upper body - trunk, arm, and hand - and flex the hip joint fully in the given direction.

The pairwise T-test was conducted on arc angles, radius, and arc areas of reach area. The result was shown in Table 2. It showed that there were no significant differences between the arc angles of the real workspace photographed by the Motion Analysis System and those of the proposed workspace (at $\alpha=0.05$), and also no significant differences between the workspace areas of the above two methods (at $\alpha=0.01$), but significant differences between radii of the two methods (at $\alpha<0.000$).

Table 2. T-test results of workspace of the upper body

Component	N	Mean	Stdev	T	P value
arc angles	6	2.572	11.163	0.56	0.60
radii	6	-10.494	1.968	-13.06	0.000
arc areas	6	1834.70	1399.463	-3.21	0.024

4.2.2. Workspace of the Lower Limb

Four angles in the right side of subject were photographed. In a seated posture, the subject initially flexed the knee joint fully and straightened out upper leg horizontally on the seat surface, and then extended the knee joint and hip joint fully.

The results of pairwise T-test showed that there were no significant differences between arc angles (at $\alpha=0.05$) and radii (at $\alpha=0.01$) of the two methods, respectively. Arc areas of the real workspace were significantly different from those of the proposed workspace at $\alpha<0.01$. These results were illustrated in Table 3.

Table 3. T-test results of workspace of the lower limb

Component	N	Mean	Stdev	T	P value
arc angles	4	0.784	20.868	0.08	0.94
radii	4	15.767	9.046	3.35	0.044
arc areas	4	1525.65	342.211	8.92	0.003

V. Conclusion

As mentioned, most past researches on reach took only arm reach in consideration. In this research, however, the general workspace generation algorithms which include trunk motion and foot reach as well as arm reach are proposed. The general workspace is very useful in real-life design process - especially in conceptual design - which includs the design of vehicle pedals, hand controls, and workplaces. In the traditional studies, only the approximate arm reach of an individual was obtained using the existing anthropometric data. This is because most of the thropometric data are presented in the form of the group of population, i.e., percentile of population. The proposed algorithms, nevertheless, can generate the workspace of each human body segment as well as arm reach of an individual, in which the individual's real anthropometric data are used.

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