A System for Evaluation of Human Upper Extremity

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A standard method to determine the shoulder range of motion in physiotherapy is to measure the declination angles in predefined planes in the glenohumeral joint. These angles can hardly be understood and visualized and they do not directly interpret the functionality of the arm. In this article, we report a computer program which computes the human arm reachable workspace based on a simplified kinematic model. The program uses as input data the values of the measured declination angles in combination with the proportions of the measured limb. It thus enables to obtain a graphic interpretation of the arm's reachability, quantifies the workspace volume and represents a platform to objectively validate the functionality of the arm. The obtained numerical and graphical results can be used for visualization, computer-aided documentation, comparison between different phases of a rehabilitation process, comparison between different subjects, and can also serve for a deeper mathematical and biomechanical analysis.

Povzetek: članek opisuje sistem za izračun dosegljivega delovnega prostora človeske roke.

1 Introduction

Objective measurements, mathematical processing of the measured data, and effective interpretations and visualizations are of crucial importance in advanced rehabilitation engineering. Many contributions with the purpose to develop new techniques of data capturing, development of new therapeutical approaches and new rehabilitation devices were reported in the literature in the area of human gait. On the contrary, there is a lack of investigations aimed to evaluate the functionality of the human upper extremity. This is primarily because the human gait can be seen as a relatively simple planar motion, while the motion of the human upper extremity is spatial and extremely difficult to evaluate and interpret.

The purpose of this investigation is to develop a computer program which computes, visualizes, and quantifies the human arm reachable workspace (AWS). The human arm reachable workspace is referred to as the volume within which all points can be reached by the chosen reference point on the wrist, namely the center point between *process styloideus ulnae* and *process styloideus radii* [1]. The AWS program is in the process of being introduced as part of a regular measurement and evaluation process of the upper extremity of (in particular hemiplegic) patients in the Institute for Rehabilitation, Ljubljana, Slovenia.

The input data to the AWS program are the arm proportions and the ranges of motion in the joints of the shoulder and of the elbow complexes as measured by the physiotherapist. At the current stage, the measurement technique in the rehabilitation center is entirely manual and only standardized selective motions are measured. The main difficulty, however, is related to the effectiveness of the computation of the workspace from the measured data since this is an extremely time-consuming numerical procedure. To make it useful and implementable on a personal computer, a very concise kinematical model of the human upper extremity must be used in the program. In this investigation, the human arm motion is seen as a combination of the shoulder and the elbow motion. The shoulder motion is composed of elementary motions in the glenohumeral, scapulothoracic, sternoclavicular, and acromioclavicular joint [2, 3, 4, 5]. In order to obtain the reachable workspace effectively, all these motions are modelled as a single spherical joint possessing three perpendicular rotation axes intersecting in the center of the human glenohumeral joint. The elbow joint is understood as a uniaxial joint connecting the ulna with the humerus and the radius with the humerus. These two joints allow the elbow flexion and extension [6] and are modelled as a single rotation. The radioulnar joint, which allows the supination and pronation of the forearm, is not included in the model since it does not influence the spatial position of the wrist.

The workspace is computed as a number of points in space and is then graphically converted into a three-dimensional body by the use of a proper computer graphics module. A physiotherapist can utilize the AWS program to compute and visualize the workspace of the injured arm and compare it with an ideal healthy arm. It is possible to numerically quantify the workspace in terms of its volume, compactness and other mathematical criteria representing the arm functionality.

The first section of this article presents the basic kinematic properties of the human upper extremity and develops a simplified kinematical model. In the following section we discuss the computation of the reachable workspace and its numerical evaluation. In the last section, an example of the treatment of a hemiplegic patient is reported.

2 Simplified kinematics

The movements of the arm are measured relatively to the arm's reference pose, which is when the upper arm is fully extended downward by the side of the body and the forearm flexed for $90°$ (placed forward in a horizontal direction) so that the palm of the hand is turned towards the body. The principal shoulder movements are shown in Figure 1. The shoulder elevation through flexion and retroflexion are measured in the sagittal plane around the coronal axis, the elevation through abduction and adduction is measured in the frontal plane around an anterior-posterior axis. The internal and external rotations are measured in the horizontal plane around a vertical axis [7, 8, 9]. The principal elbow movement is the flexion-extension which is measured in the sagittal plane.

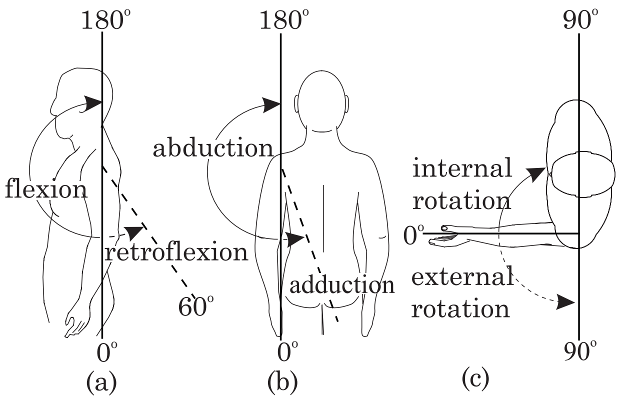

Figure 1: The shoulder complex movements: The elevation through flexion - retroflexion (a), the elevation through abduction - adduction (b) and the internal - external rotation (c).

Figure 2 presents a kinematical model of the arm that replicates the motion characteristics of each single joint included in the arm [5, 6, 10]. Here, U denotes the universal joint that contains two perpendicular rotations, S is the spherical joint that contains three perpendicular rotations, joint T is a translation and joint R a rotation. In the shoulder girdle, the sternoclavicular joint *Sc* is modelled as an universal joint, the acromioclavicular joint *Ac* as a spherical joint, and the scapulathoracic joint *St* as two translations and one rotation. The rest of the shoulder motion is concentrated in the glenohumeral joint *Gh* which is spherical.

The sum of the degrees of freedom in the shoulder girdle is $f = 8$. The number of movable segments is $N = 4$ and the number of joints is $n = 5$. In accordance to the

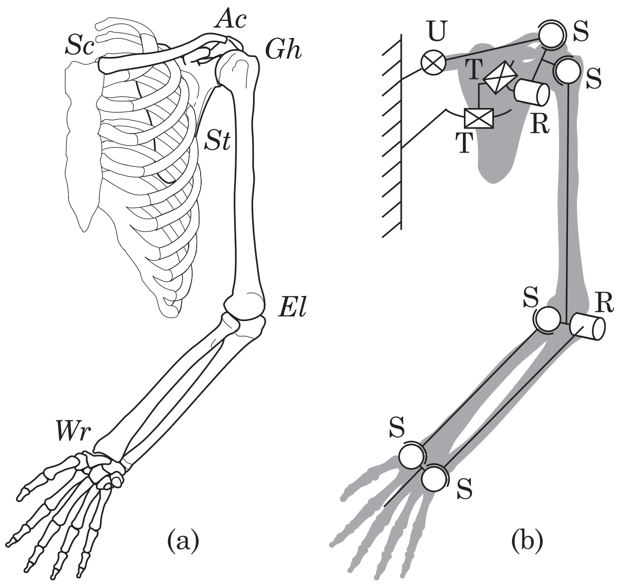

Figure 2: The shoulder complex joints *Sc, Ac, St, Gh*, the elbow *El*, and the wrist *Wr* (a) kinematical model (b).

Grübler's formula only

$$F = \lambda(N - n) + f = 6(4 - 5) + 8 = 2$$

degrees of freedom are independent ($\lambda = 6$ is used since the girdle's motion is spatial). One can see that these two independent degrees of freedom are rotations, meaning that the primary function of the girdle is to point the glenohumeral joint in space. The same motion can be obtained by using only an universal joint U as shown in Figure 3a. If there is a need to also replicate the changing of the size of the girdle, we have to additionally include a dependent translation T which depends on the rotations in the girdle's U joint [11].

In a similar way, we can analyze the kinematical structure of the elbow joint and of the wrist. The ulna is attached to the humerus by a rotational joint R and the radius by a spherical joint S. On the other end, the bones of ulna and radius are attached to the hand by two spherical joints S (Figure 2b). The presented forearm mechanism contains $N = 3$ movable links (the hand is considered as a single rigid link) and $n = 4$ joints. The sum of degrees of freedom in these four joints is f=10. The Grübler's formula gives

$$F = \lambda(N - n) + f = 6(3 - 4) + 10 = 4$$

independent degrees of freedom. They can be replaced by two independent U joints and, eventually, a dependent translation T that models the changing in distance of the forearm (Figure 3a). However, the position of the wrist depends only on the elbow flexion-extension, so that only one degree of freedom (rotation) is needed to model the elbow complex when computing the reachable workspace (Figure 3b). Other three are, therefore, neglected.

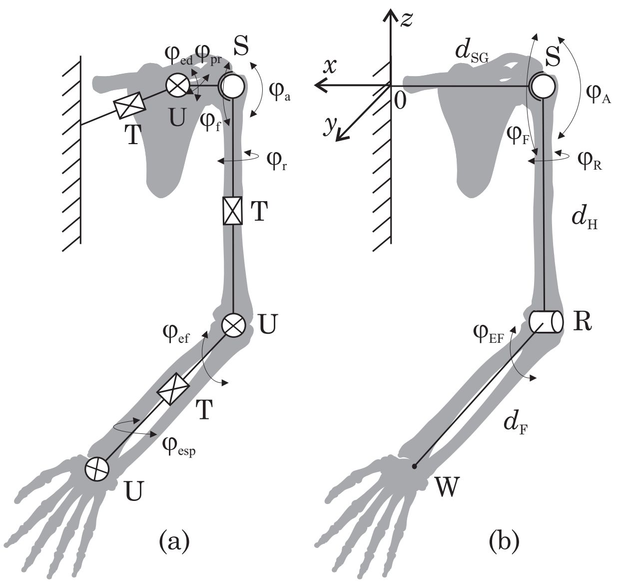

Figure 3: A functional kinematical model (a) and a simplified kinematical model (b) of the arm.

By comparing the joint arrangements in (Figure 3a) with the functional movements of the human arm, it is possible to observe that the first two rotations φ_{ed} and φ_{pr} represent the elevation-depression and the protraction-retraction of the shoulder girdle with the center in the sternoclavicular joint *Sc*. Angles φ_{a}, φ_{f} and φ_{r} represent the humeral abduction-adduction, flexion-retroflexion and internal-external rotations with the rotation center in the glenohumeral joint *Gh*. In order to compute the arm workspace effectively, the movements in the shoulder complex can additionally be simplified by producing the sum of movements in the girdle and in the glenohumeral joints. Thus, the arm elevation through abduction φ_{A}, elevation through flexion φ_{F} and rotation φ_{R} are combined by motions in the shoulder girdle and in the glenohumeral joint. For the sake of simplicity it is also assumed that the rotation center is fixed in glenohumeral joint. The final model is seen in Figure 3b.

The complex anatomical properties of the arm do not directly correspond to the presented arrangement of simple rotations about fixed axes [1, 12, 13, 14]. In such a model, therefore, one has to include the interdependencies between the joint coordinates. The lower and the upper limits of joint angles depend on the values of other joint angles. Also the length of the shoulder segment, of the upper arm and of the forearm are dependent on the motions in the simplified joints. Based on the measurements of a number of healthy subjects the correlations between joint coordinates were identified in the past [1].

The simplified model, as presented in Figure 3b, is a very rough approximation of the human arm kinematics. It primarily represents the spatial motion of the reference point W on the wrist. The model includes three rigid segments, the shoulder girdle segment d_{SG} representing the clavicula and scapula, the upper arm segment d_{H} representing the humerus, and the forearm segment d_{F} representing the radius and ulna. We fixed the origin of the reference coordinate inside the body in the region of sterna (Figure 3b). In the reference pose of the arm, when all joint angles are zero, the shoulder segment is parallel to x (medial direction), the upper arm segment to z (vertical direction) and the forearm segment to y (anterior direction). Thus, the segment vectors for the left arm are

$$\mathbf{r}_{\mathrm{SG}} = (-d_{\mathrm{SG}}, 0, 0)^{\mathrm{T}}, \quad (1)$$

$$\mathbf{r}_{\mathrm{H}} = (0, 0, -d_{\mathrm{H}})^{\mathrm{T}}, \quad (2)$$

$$\mathbf{r}_{\mathrm{F}} = (0, d_{\mathrm{F}}, 0)^{\mathrm{T}}. \quad (3)$$

There are three rotations in the glenohumeral joint. The elevation through flexion-extension is expressed as a rotation about axis x. The rotation matrix is

$$\mathbf{R}_{\mathrm{F}} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\varphi_{\mathrm{F}} & -\sin\varphi_{\mathrm{F}} \\ 0 & \sin\varphi_{\mathrm{F}} & \cos\varphi_{\mathrm{F}} \end{bmatrix}. \quad (4)$$

The elevation through abduction-adduction is a rotation about axis y and the rotation matrix is

$$\mathbf{R}_{\mathrm{A}} = \begin{bmatrix} \cos\varphi_{\mathrm{A}} & 0 & \sin\varphi_{\mathrm{A}} \\ 0 & 1 & 0 \\ -\sin\varphi_{\mathrm{A}} & 0 & \cos\varphi_{\mathrm{A}} \end{bmatrix}. \quad (5)$$

The internal external rotation is modelled as a rotation about axis z and the corresponding rotation matrix is as follows

$$\mathbf{R}_{\mathrm{R}} = \begin{bmatrix} \cos\varphi_{\mathrm{R}} & -\sin\varphi_{\mathrm{R}} & 0 \\ \sin\varphi_{\mathrm{R}} & \cos\varphi_{\mathrm{R}} & 0 \\ 0 & 0 & 1 \end{bmatrix}. \quad (6)$$

It is assumed in this model that the limits of angle φ_{A} are constant and independent of other coordinates so that its range is as follows

$$\varphi_{\mathrm{A}} = [\varphi_{\mathrm{Am}}, \varphi_{\mathrm{AM}}], \quad (7)$$

where φ_{Am} and φ_{AM} are measured in the reference pose of the arm. The limits of the elevation through flexion-extension are linear functions of the elevation through abduction-adduction angle [1]. The range of this coordinate varies as follows

$$\varphi_{\mathrm{F}} = [\varphi_{\mathrm{Fm}} + \varphi_{\mathrm{A}}/3, \varphi_{\mathrm{FM}} - \varphi_{\mathrm{A}}/6], \quad (8)$$

where φ_{Fm} and φ_{FM} are measured in the reference pose of the arm. The limits of the internal and external rotation have a quadratic relationship with the elevation through abduction-adduction and flexion-extension angle [1]. Its range varies within the following values

$$\varphi_{\mathrm{R}} = [\varphi_{\mathrm{Rm}} + 7\varphi_{\mathrm{A}}/9 - \varphi_{\mathrm{F}}/9 + 2\varphi_{\mathrm{A}}\varphi_{\mathrm{F}}/810, \\ \varphi_{\mathrm{RM}} + 4\varphi_{\mathrm{A}}/9 - 5\varphi_{\mathrm{F}}/9 + 5\varphi_{\mathrm{A}}\varphi_{\mathrm{F}}/810], \quad (9)$$

where φ_{Rm} and φ_{RM} are measured in the reference pose of the arm. In Equations 8,9 the angles are expressed in degrees.

The elbow flexion-extension rotation is calculated as a rotation about axis x and the corresponding rotation matrix is

$$\mathbf{R}_{\mathrm{EF}} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\varphi_{\mathrm{EF}} & -\sin\varphi_{\mathrm{EF}} \\ 0 & \sin\varphi_{\mathrm{EF}} & \cos\varphi_{\mathrm{EF}} \end{bmatrix}. \qquad (10)$$

It is assumed that the limits of this angle are constant and independent on other coordinates so that its range is as follows

$$\varphi_{\mathrm{EF}} = [\varphi_{\mathrm{EFm}}, \varphi_{\mathrm{EFM}}]. \qquad (11)$$

Here, $\varphi_{\mathrm{EFm}} = -90°$ and $\varphi_{\mathrm{EFM}} = 60°$ are fixed as for the healthy elbow [1, 7, 8].

The position of the reference point W is calculated by

$$\mathbf{r}_{\mathrm{W}} = \mathbf{r}_{\mathrm{SG}} + \mathbf{R}_{\mathrm{R}} \cdot \mathbf{R}_{\mathrm{A}} \cdot \mathbf{R}_{\mathrm{F}} \cdot \mathbf{r}_{\mathrm{H}} + \mathbf{R}_{\mathrm{EF}} \cdot \mathbf{r}_{\mathrm{F}}. \qquad (12)$$

3 Workspace computation

The input data to the AWS program are the joint limits measured in the reference pose of the arm, which are φ_{Am}, φ_{Fm}, φ_{Rm}, φ_{EFm}, φ_{AM}, φ_{FM}, φ_{RM}, and φ_{EFM}. These parameters vary considerably among individuals as affected by age, sex, injuries, and stage of the illness [7]. Relatively to the hight of the subject H, the segments of the arm are normalized in accordance to the anthropometric table [15]. The length of the shoulder girdle length is then $d_{SG} = 0,129 \cdot H$, of the humerus is $d_H = 0,185 \cdot H$, and of the forearm $d_F = 0,146 \cdot H$.

The procedure to determine the workspace has few stages. The first stage is to compute the set of points which can be reached by the wrist. This computation involves four nested loops, each associated with one joint angle. In every iteration, position $\mathbf{r}_{\mathrm{W}}$ (Equation 12) is computed and stored as a three dimensional vector. The procedure is repeated until all ranges of joint angles are swept [1]. In addition, the collisions between the segments of the arm (humerus and forearm) and the body (head, neck and trunk) have to be taken into account. If during the computation an arm segment intersects the body, the related position of the wrist is eliminated as impossible and is not considered as part of the workspace. An elliptical cylinder to approximate the body whose size is $0,174 \cdot H$ in the frontal plane and $0,089 \cdot H$ in the sagittal plane is used. The head is approximated by a sphere whose radius is $0,065 \cdot H$ [15].

The resolution is set to 5° for all joint angles. It corresponds to the measurement error in the input data. Since the ranges of coordinates change from one subject to another and throughout the workspace, it is impossible to exactly predict the number of iterations. Usually, tens of thousands of iterations are needed to determine the whole set of points approximating the reachable workspace.

The obtained set of points lies inside a cube of edge $L = 2(d_{\mathrm{H}} + d_{\mathrm{F}})$ whose center is in the center of the shoulder joint. This cube is seen as a volume of n^3 smaller cubes with edge L/n, where n is a desired resolution, which is limited by

$$L/n > (d_{\mathrm{H}} + d_{\mathrm{F}}) \tan 5°. \qquad (13)$$

The cubes that do not contain at least one point $\mathbf{r}_{\mathrm{W}}$ are eliminated. As a result, the workspace of the arm is described by a set of cubes of edge L/n.

In order to increase the accuracy, the cubes forming the surface of the workspace are broken into smaller ones with edge of half length. In every step i the workspace volume is computed by

$$V^i = V_{\mathrm{I}}^i + \frac{V_{\mathrm{S}}^i}{2}, \qquad (14)$$

where V_{S} is the volume of cubes on the surface, and V_{I} the volume of all other (inner) cubes. The procedure is ended when

$$\nu^i = \frac{|V^i - V^{i-1}|}{V^{i-1}} \qquad (15)$$

is smaller than a prescribed value ν.

The last stage in determining the arm workspace is to smoothing the surface cubes. For this purpose a Bezier interpolation [16] is performed. The workspace can thus be visualized with different color textures, illuminated with different positions of light, or made transparent.

A comparison between the calculated and the measured reachable workspace of the healthy left arm is shown in Figure 4. The workspace in Figure 4a was measured in equidistant planes in [1]. Such a measurement is extremely complicated and time consuming. It can only be performed on healthy subjects. On the contrary, the calculated workspace (Figure 4b) can be obtained based on very simple manual measurements which are part of a standard procedure in treating hemiplegic patients in the rehabilitation center. The similarity between the measured and the calculated workspace is quite evident.

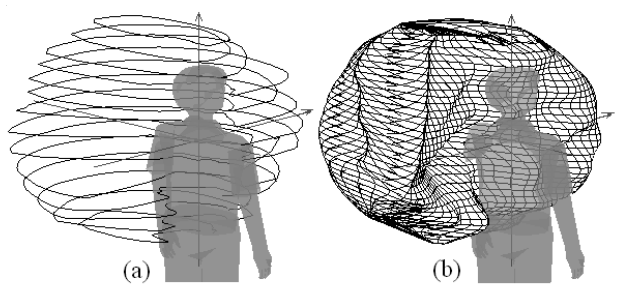

Figure 4: A comparison between the measured (a) and the calculated (b) reachable workspace.

4 Example

An example of a treatment of a hemiplegic patient is presented in Figure 5. The figure shows the reachable workspace of the left handicapped arm before the treatment

(W_{L1}) and two different phases during the treatment (W_{L2} and W_{L3}). Workspace W_{R0} is associated with the healthy right arm inverted to the left hand side for comparison. The measured ranges of motion are collected in Table 1.

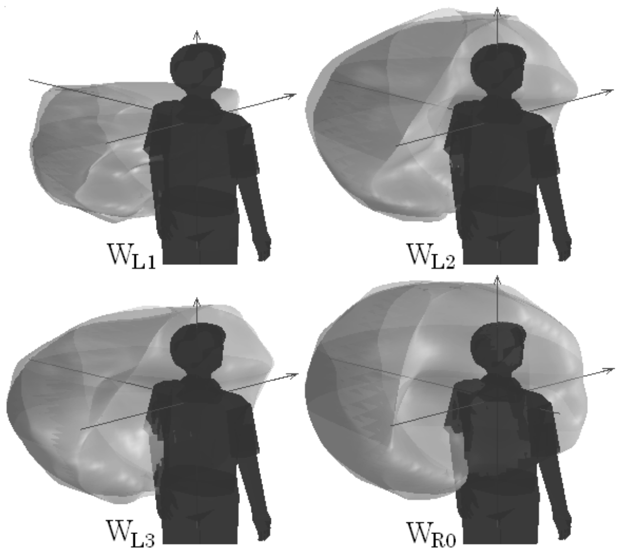

Figure 5: A comparison of the reachable workspace of the left handicapped arm with the reachable workspace of the right healthy arm of a hemiplegic patient.

The measured ranges of motion of the handicapped left shoulder before and during the treatment, as well of the healthy right shoulder, are reported in Table 1. The elbow flexion-extension angles are taken as for the healthy arm and are $\varphi_{\mathrm{EFm}} = -90°$ and $\varphi_{\mathrm{EFM}} = 60°$.

Table 1: The measured shoulder ranges

	φ_{Fm} φ_{FM}	φ_{Am} φ_{AM}	φ_{Rm} φ_{RM}
W_{L1}	$-45°$ $65°$	$-10°$ $80°$	$-55°$ $25°$
W_{L2}	$-55°$ $140°$	$-10°$ $95°$	$-60°$ $40°$
W_{L3}	$-80°$ $120°$	$-10°$ $95°$	$-45°$ $50°$
W_{R0}	$-60°$ $170°$	$-10°$ $170°$	$-60°$ $90°$

Table 2 shows the computed volume of the reachable workspace of the handicapped left arm and of the healthy right arm. The workspace was computed with $\nu \leq 10\%$ relative error. The hight of the subject is $180,0$ cm.

Note the workspace volume is not directly associated with functionality of the arm. Other indices in combination with the volume can be used, such as the workspace compactness [17]. The workspace compactness quantifies the similarity of the workspace shape with a sphere. It is assumed that a compact workspace is more adaptable then an elongated one. Also the location of the workspace relative to the body is an important issue. A reachable space in front of the body could in general be more useful.

Table 2: The computed workspace volume for $H = 18,00$ dm

	volume $\pm\nu$
W_{L1}	$190,4\ \mathrm{dm}^3$
W_{L2}	$401,4\ \mathrm{dm}^3$
W_{L3}	$364,3\ \mathrm{dm}^3$
W_{R0}	$598,2\ \mathrm{dm}^3$

The AWS program is written in Matlab and converted into an autonomic form. It is designed to be used at the Institute for Rehabilitation as a standard tool for the examination of the shoulder complex. The input data form contains an identical information as the paper form used in the past. The workspace block is added (Figure 6).

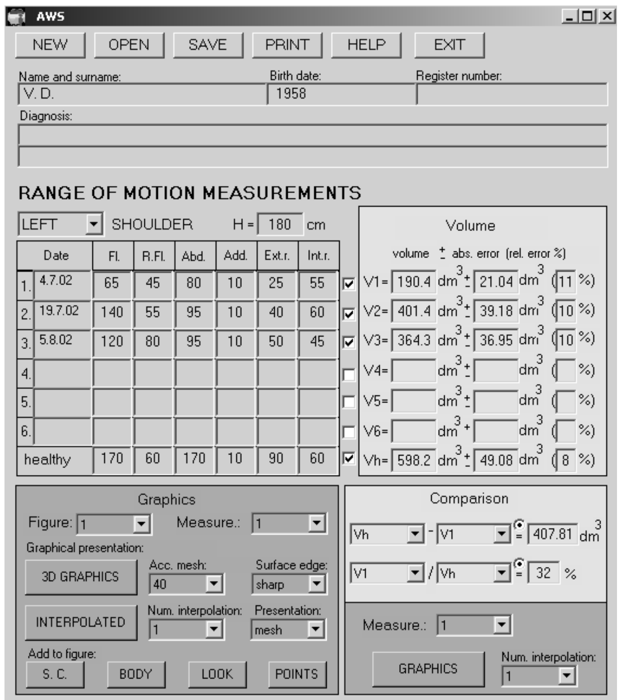

Figure 6: The input form of the AWS program.

The workspace is visualized in a posterior and in an anterior view. It is possible to superimpose the workspace of the handicapped arm onto the one of the healthy arm by using a transparent envelope (Figure 7). Thus, the workspaces can be directly compared during different phases of the rehabilitation process. The results can easily be documented and stored in a computer or printed. They can be displayed and numerically processed, as well as electronically transferred to another user.

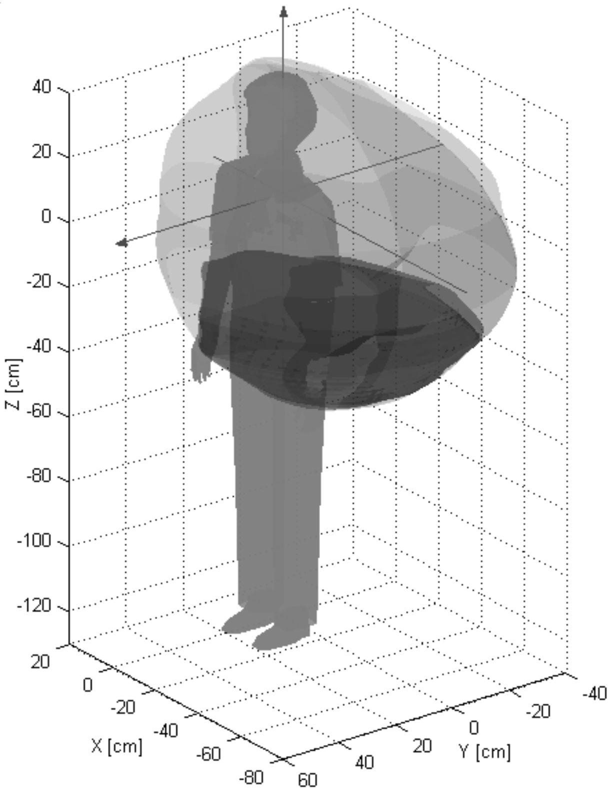

Figure 7: A direct comparison of the workspace of the handicapped arm (W_{L1}) with the one of the healthy arm (W_{R0}) by superimposing the two workspaces.

5 Conclusion

A computer program which computes the human arm reachable workspace is reported in this article. The program is based on a simplified kinematic model of the human upper extremity in which the shoulder complex is approximated by a spherical joint and the elbow complex by a rotation. The input data to this program are taken from a standard evaluation procedure in physiotherapy. The reachable workspace can be quantified by its volume or other mathematical indices.

The main advantage of this program is that it can visualize the reachability of the measured human arm. The obtained results can be used for computer-aided documentation, numerical or visual comparison between different phases of a rehabilitation process, and numerical or visual comparison between different subjects. This helps us to plan and control the rehabilitation procedure of shoulder patients. The program is now being introduced in the Institute for Rehabilitation, Ljubljana, Slovenia.

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